

Signalling Relays

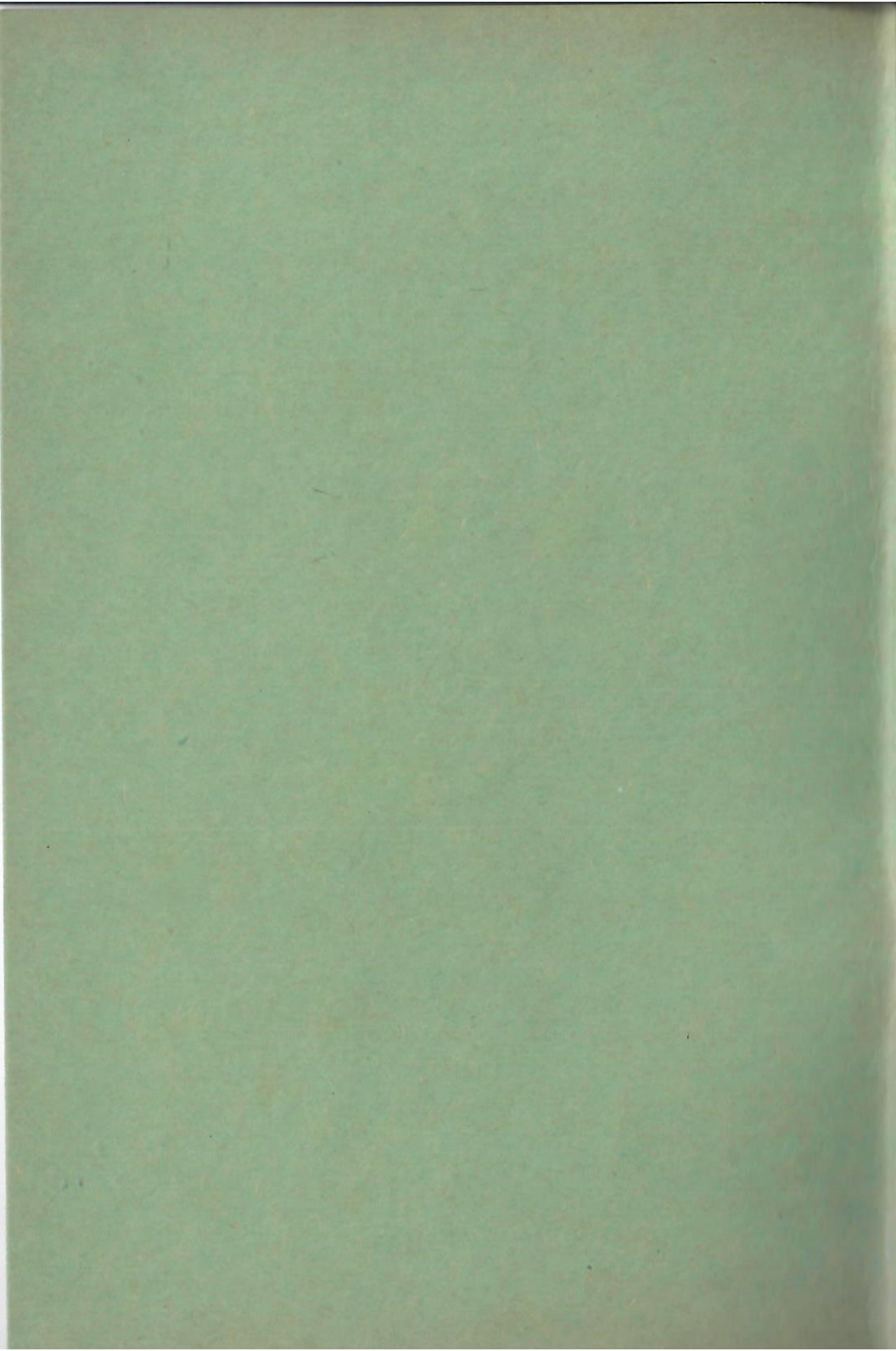
(British Practice)

J. F. H. TYLER, B.Sc. (Eng.)



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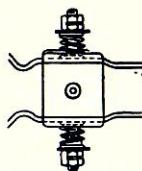


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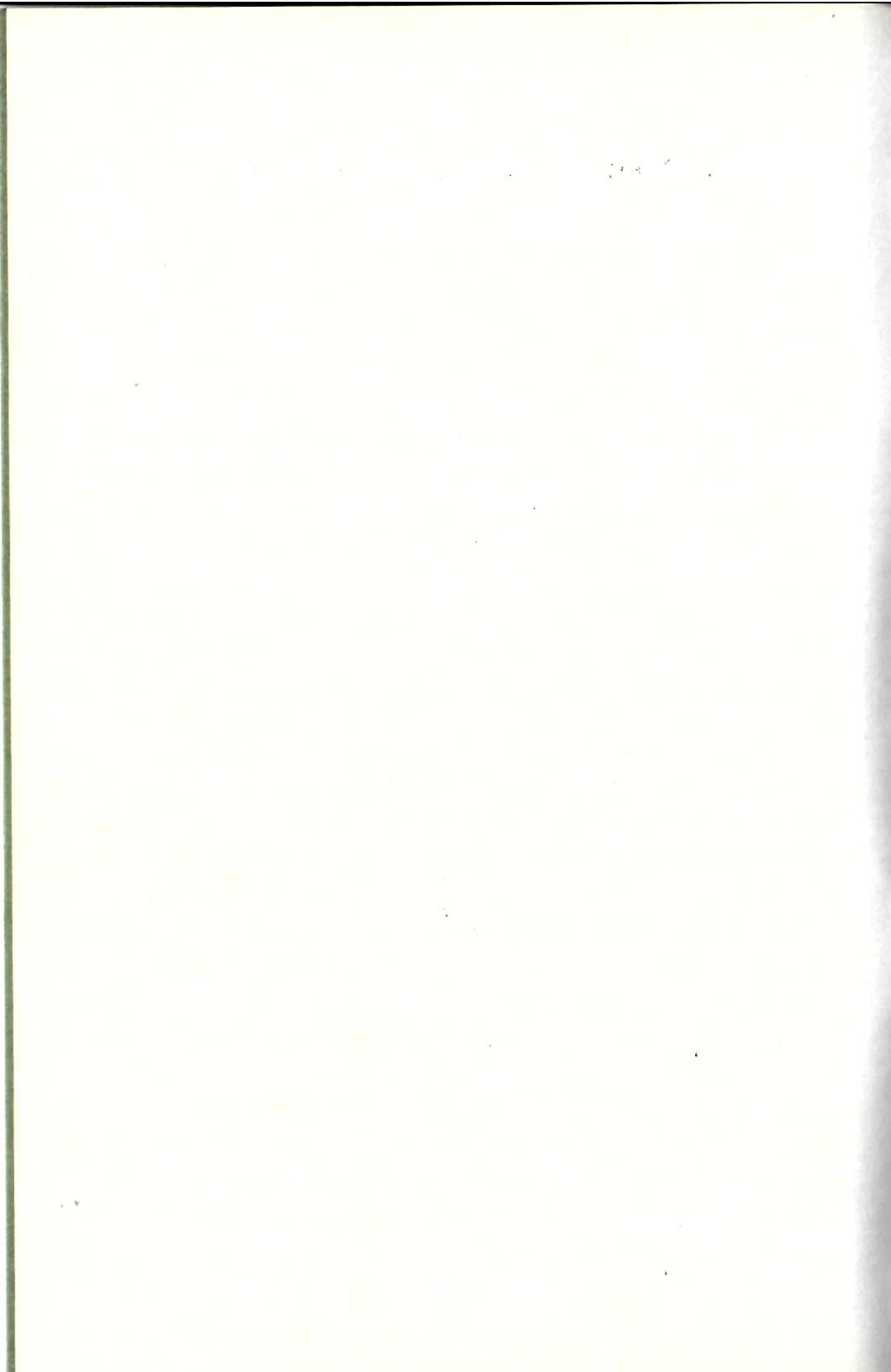
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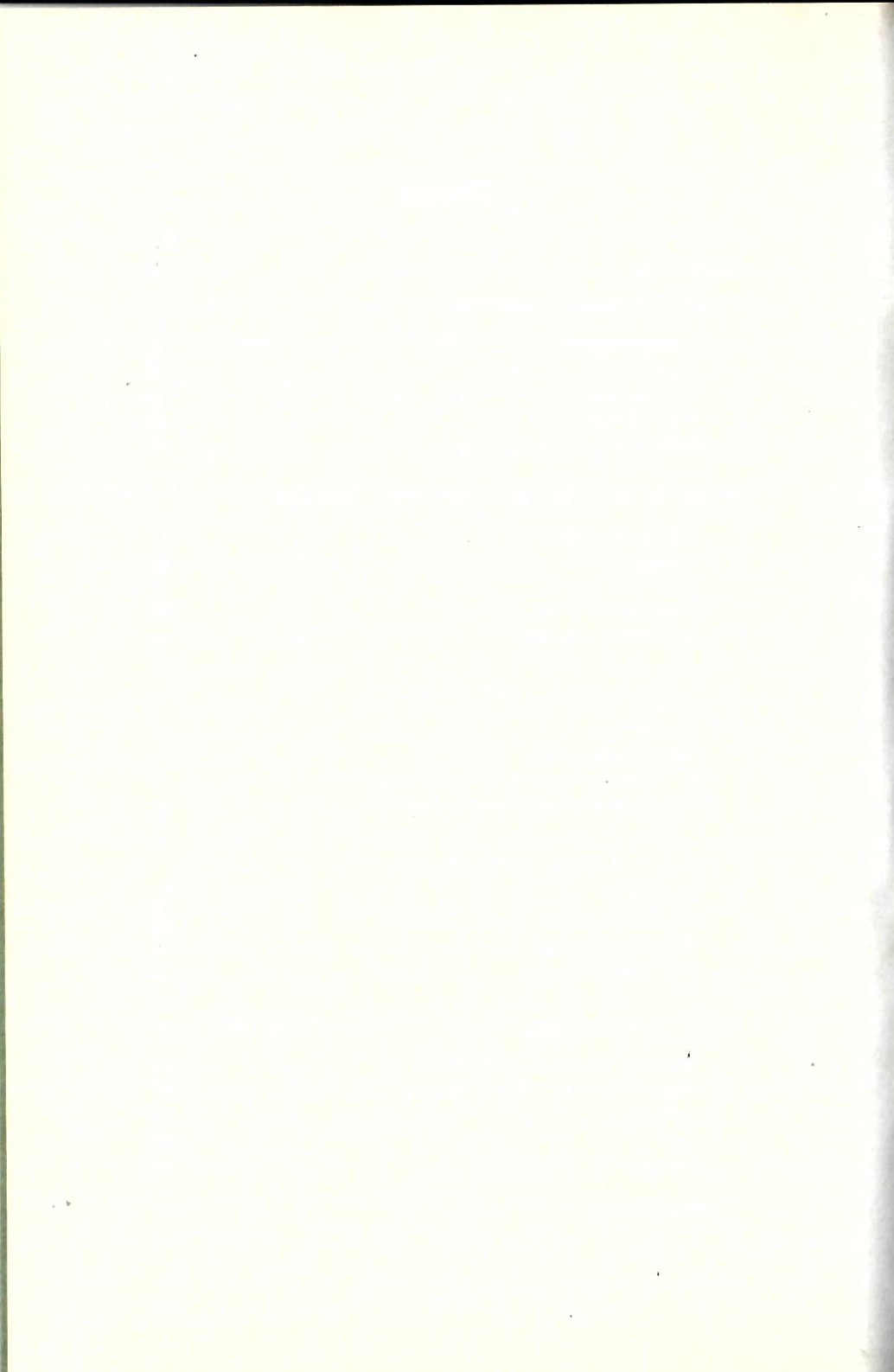
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SIGNALLING RELAYS

INTRODUCTION

A relay is an electrically-operated device for opening and closing circuits. In modern railway signalling, relays take a variety of form according to the type of Circuit in which they are to operate and the function to be controlled.

This booklet describes the main types of relay in general use and the principles on which they operate.

Relays used in signalling circuits are of the electro-magnetic type and consist essentially of an operating coil or coils which, when energised, set up a magnetic field which causes contacts to be operated.

Constructionally and electrically, relays may be divided into d.c. and a.c. types because the means by which the electrical energy in the coils is converted into mechanical energy in order to move the contacts are fundamentally different. In d.c. types, the contacts are carried on an armature forming part of a magnetic circuit in which a field is set up by the current in the coils. In a.c. types, the contacts are attached by a link mechanism to a metal sector, disc or cylinder in which currents are induced by the alternating magnetic field produced by the current in the coils.

Whilst every endeavour has been made to explain the action of each type of relay in the simplest possible manner, it has been thought desirable that statements made should occasionally have a mathematical foundation. This is particularly so in the case of a.c. relays, the operating principles of which cannot be thoroughly grasped without a knowledge of phase relationships. The student to whom vector diagrams are still somewhat of a mystery will find that in all cases the essential operating principles are explained in simple language before an excursion is made into mathematics or vector diagrams and it is hoped that his interest in the subject will be raised sufficiently to encourage him to probe deeper into those subjects elsewhere.

The Student should read the relevant specifications published by the British Standards Institution which contain much interesting data on relays.

D.C. RELAYS

Symbols used in the Text

Magnetic Circuit

- Φ = total flux in lines
N = number of turns on the coils
I = coil current in amps.
 μ = permeability of the iron
l = length in cms. of the particular part of the magnetic circuit
a = cross-sectional area in sq. cms. of the particular part of the magnetic circuit
F = pull on armature in dynes
B = flux density in lines per sq. cm.
 $\propto$ = is proportional to

Transient Conditions

- E = applied voltage
 L_1 = Inductance in henries when relay in de-energised position
 L_2 = Inductance in henries when relay in energised position
i = instantaneous current in amps.
R = Resistance of coil in ohms
t = time in seconds since the transient commenced
e = 2.7183

Inductance

A circuit has an inductance of 1 henry when an E.M.F. of 1 volt is induced by a current varying at the rate of 1 amp./second.

For a magnetic circuit of constant reluctance S, the flux ϕ corresponding to a current i is

$$\phi = \frac{1.257 N i}{S}$$

$$\text{The self-induced voltage } e^L = - \frac{N}{10^8} \frac{d\phi}{dt}$$

$$\begin{aligned} \therefore e^L &= - \frac{1.257 N^2}{S \times 10^8} \frac{di}{dt} \\ &= - L \frac{di}{dt} \end{aligned}$$

PART I

D.C. RELAYS

1. General

All d.c. relays operate on the tractive-armature principle ; the following types being in general use :—

- 1—Neutral
- 2—Polar
- 3—Neutral-polar

The operation of the neutral relay should be clearly understood before proceeding to a consideration of the other types.

2. Neutral Relays

Neutral relays are so-called because the magnetic circuit is constructed of soft iron having low retentivity ; that is, it does not retain its magnetisation to any extent after current ceases to flow in the magnetising (or operating) coils. The coils may therefore be energised in either direction to operate the relay.

Fig. 1 shows the magnetic circuit of a simple neutral relay.

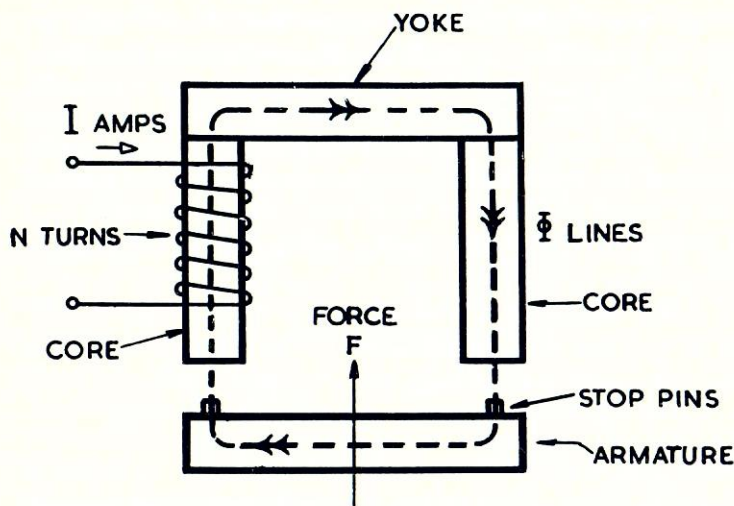


FIGURE 1.

DIAGRAMMATIC REPRESENTATION OF THE MAGNETIC CIRCUIT
OF A D.C. NEUTRAL RELAY

The pull on the armature is proportional to the square of the flux density in the air gaps between the core and the armature. The flux density is the total flux divided by the cross sectional area of the gap.

The flux has a path round the whole magnetic circuit which consists of the core, the air gaps and the armature. The flux path is thus partly iron and partly air.

To produce the flux requires magnetomotive force or M.M.F. which may be considered as being divided between that required for the iron portion and that required for the air portion. For the same length of magnetic circuit, however, considerably less M.M.F. is required for iron than for air and the ratio of these M.M.F.'s is known as the permeability of the iron which is given the symbol μ .

Now the value reached by the M.M.F. depends on the number of turns on the coil and the current flowing in it. In other words, the M.M.F. is produced by ampere-turns (amps. $\times$ turns) on the coil which may also be divided into the amp.-turns required for the iron portion and the amp.-turns required for the air portion. As the number of turns on the coil is fixed by the designer, it will now be understood that, for a given relay, the pull on the armature is proportional to the square of the current in the coils but this statement can only be true if the air gap remains unaltered, which unfortunately it does not, since the air gap when the armature has closed is obviously less than when it is open. The current in the coils remains the same and so the pull on the armature is greater because there is more flux in the magnetic circuit. This is an important point in d.c. relay operation.

Consider the matter more scientifically. In text books it is stated that

$$\text{Flux} = \frac{\text{Magneto Motive Forces}}{\text{Reluctance}}$$

$$\text{or } \Phi = \frac{1.257 \text{ NI lines}}{\frac{\mu l}{a}} \quad (1)$$

It is also proved that the force produced by an electro-magnet on its armature is

$$F = \frac{B^2 a}{8\pi} \quad \text{dynes} \quad (2)$$

Now if N_1, l_1 , refer to the iron part of the magnetic circuit and N_2, l_2 , to the air part and if we assume the cross sectional area of the iron to be uniform throughout, it can be easily shown that

$$\text{for the iron part, } N_1 I = \frac{l_1 B}{1.257 \mu}$$

$$\text{and for the air part, } N_2 I = \frac{l_2 B}{1.257}$$

$$\begin{aligned} \text{But } NI &= N_1 I + N_2 I \\ \therefore NI &= \frac{B}{1.257} \left[\frac{l_1 + l_2}{\mu} \right] \end{aligned}$$

$$\text{Now from (2), } B = \sqrt{\frac{8\pi F}{a}}$$

$$\text{Hence } NI = \frac{1}{1.257} \sqrt{\frac{8\pi F}{a}} \times \left[\frac{l_1 + l_2}{\mu} \right]$$

which means that F is proportional to $\frac{(NI)_2}{\left[\frac{l_1 + l_2}{\mu} \right]^2}$

This expression shows clearly that the armature force is proportional to the square of the current. This means that in order to double the force, the current must be increased $\sqrt{2}$ (or 1.414) times. It also shows the effect of altering the air gap. If l_2 is reduced (as is the case when the relay has picked up), F becomes greater.

In fig. 2, Curve A is the magnetisation curve for the iron and is for all practical purposes a straight line up to the saturation point (which is never reached in normal operation). This incidentally means that the permeability μ is constant up to that point—it reduces thereafter. Curve B is the magnetisation curve for the open air gap which is a straight line throughout because μ for air is 1. Curve C is the resultant magnetisation curve of the whole magnetic circuit of the relay and for a given force (or flux density), is the sum of the amp.-turns for the iron part and the amp.-turns for the air gap.

When the front contacts are open, the force required to pick up the armature is shown on Curve C to be F_1 but after the armature has operated, it will be separated from the core by the

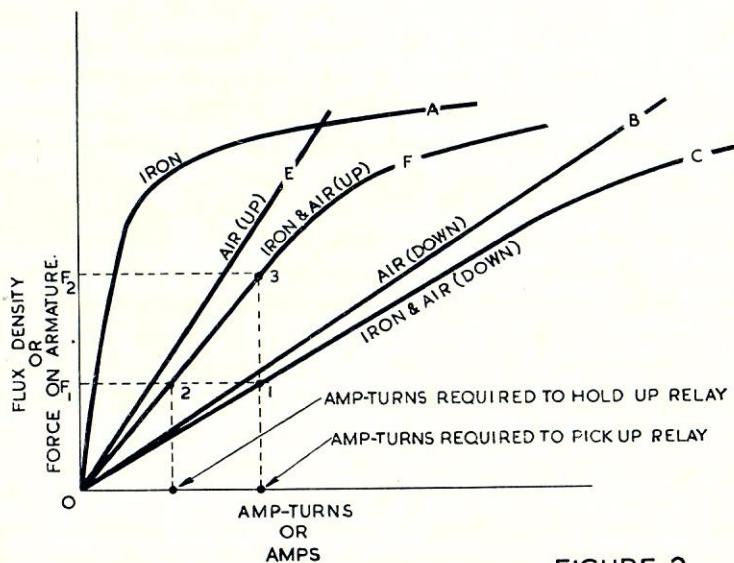


FIGURE 2.

MAGNETISATION CURVES OF D.C. NEUTRAL RELAY

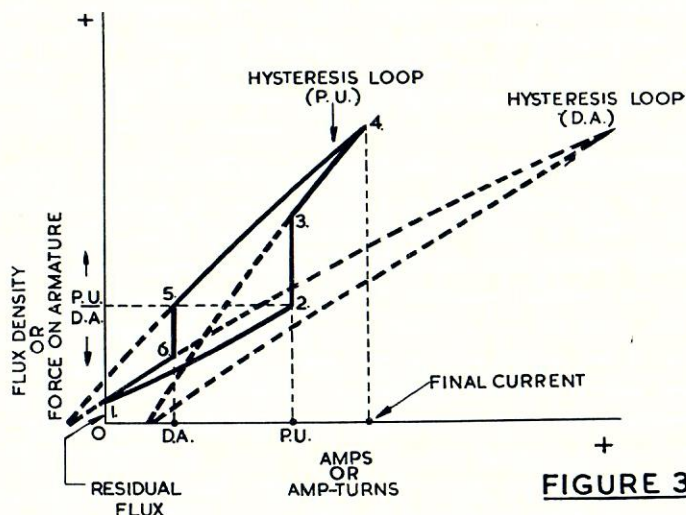


FIGURE 3

EFFECT OF HYSTERESIS IN RELAY IRON

stop (or residual) pins only. In this position the amp.-turns required to maintain the armature is less as indicated by the dotted line from 1 on Curve C to 2 on Curve F, but actually the current in the coils is unaltered and so the force on the armature is greater than is required, as indicated at 3 on Curve F. Part of this extra force is used to flex the front contacts sufficiently to give good contact pressure which imposes an additional load on the armature when it is in the energised position.

In order to release the armature, it is necessary to reduce the amp.-turns to a point where the force is less than F_1 , that is from 3 to 2 along Curve F.

Thus it is seen why fundamentally, the current required to release a d.c. relay is always less than that required to pick it up. Although primarily due to the alterations in the air gap, the difference between the pick-up and drop-away currents is increased by hysteresis in the relay iron. Fig. 3 shows in more detail how the flux density varies during the operation and release of the relay. The figure had been distorted for clarity. In the de-energised condition there will be a small residual flux in the core. When a voltage is applied to the coils, the current in rising to its steady value first causes the flux to rise from 1 to 2 along the curve. At this point the flux density will be sufficient to cause the armature to be moved and reduce the air gap ; the flux will then rise to 3 and continue to 4 which corresponds to the steady current in the coils. When the voltage is disconnected, the current in falling causes the flux to fall from 4 to 5 along the curve. At this point the flux density will fall below the value required to maintain the armature which will release, thus increasing the air gap and reducing the flux to 6. Finally the flux will decrease from 6 to 1 where the current will again be zero.

The difference between the pick-up current and the drop-away current should be as small as practicable in track relays to ensure good shunting characteristics. This is achieved firstly by the choice of good quality relay iron and secondly by having as small an air gap change as is practicable. The air gap in the energised position cannot be eliminated because, if it were, the residual flux mentioned earlier might cause the armature to be retained when the supply is disconnected. For this reason, stop (or residual) pins are provided to ensure a definite minimum air gap in the energised position.

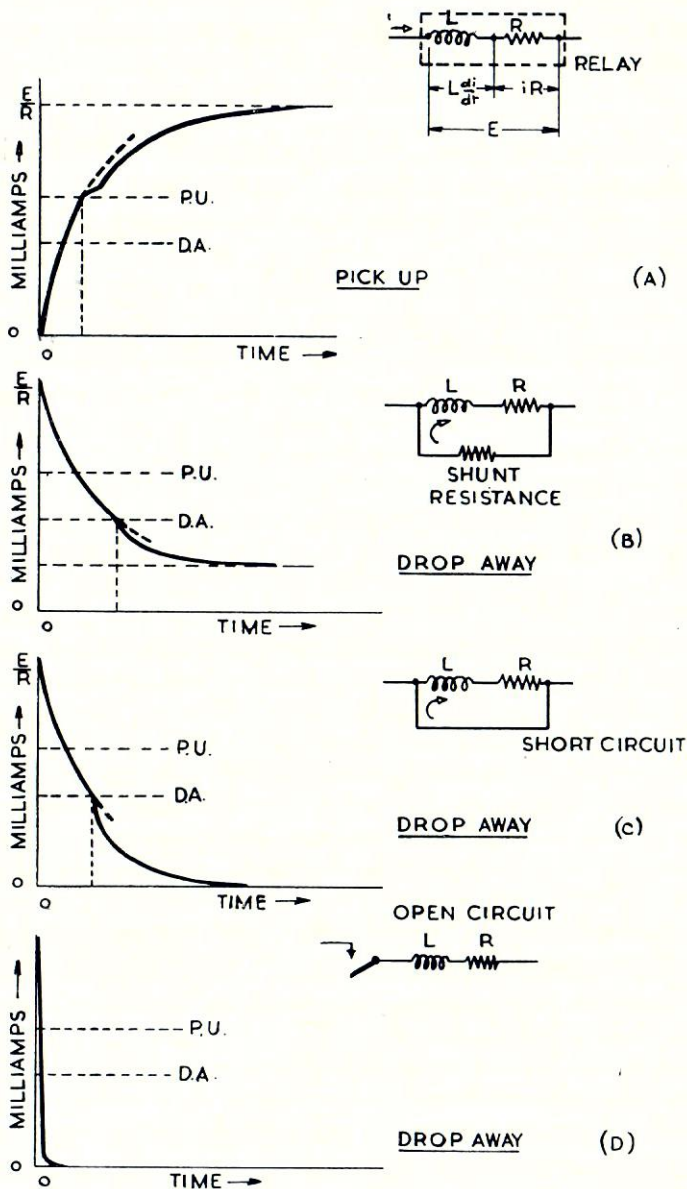


FIGURE 4

COMPARISON OF OPERATING AND RELEASING TIMES OF D.C. NEUTRAL RELAY UNDER VARIOUS CONDITIONS

It has been hinted earlier that when the voltage is applied to or disconnected from the coils, it takes some little time before the current becomes steady. These are known as transient conditions and are important so far as track relays are concerned.

When the voltage is first applied to the coils, the magnetic flux in rising, cuts the turns on the coils and in so doing produces a back E.M.F. which opposes the applied voltage and retards the growth of current. Fig. 4 shows the equivalent circuit and, as shown in text books, the applied voltage

$$E = L_1 \frac{di}{dt} + iR \dots\dots\dots(3)$$

from which it can be shown that the current, t seconds after the voltage has been applied, is in accordance with the expression

$$i = \frac{E}{R} \left(1 - e^{-\frac{Rt}{L_1}} \right) \dots\dots\dots(4)$$

When the current reaches the pick-up value, the armature closes and the inductance is increased to L_2 because, due to the reduced air gap, the flux per amp. is increased. The increase in flux increases the back E.M.F. during the movement of the armature after which the current continues to rise along a new curve corresponding to the increased inductance, until it reaches the final value $\left(\frac{E}{R} \right)$. This process is indicated in fig. 4A.

When the relay is disconnected the current is obviously reduced to zero immediately but the flux decays comparatively slowly owing to the eddy currents, produced in the core by the rapid flux change, which tend to maintain the flux. The drop-away time, on a disconnection is, however, generally negligible. (See fig. 4D).

If, on the other hand, the relay releases due to the reduction in current from say I_2 to I_1 , caused by the application of a shunt resistance (as in the case of a track relay), the time taken as shown in fig. 4B, although a matter of milliseconds, is much longer than if the relay were simply disconnected. In this case the current decays in accordance with the expression

$$i = I_1 + (I_2 - I_1)e^{-\frac{Rt}{L_2}} \dots\dots\dots(5)$$

The rate of rise or fall of current during transient conditions is also dependent on exterior circuit values because L and R apply

to the whole circuit and not only to the relay itself. If the applied shunt resistance is negligible the current decay expression becomes

$$i = \frac{E}{R} e^{-\frac{Rt}{L_2}} \dots \dots \dots (6)$$

Owing to the production of eddy currents in the core the flux will decay at a slower rate than the current so that the actual release time will be a little longer than it takes the current to fall to the release figure. (See fig. 4C).

The time taken by the armature to travel between the front and back contacts is also a factor to be considered. Before the release movement commences, the front contacts are applying pressure to the armature, tending to force it away from the core. When the relay current is interrupted (or the shunt is applied), the contact pressure, which is now assisting to accelerate the armature, reduces as the armature moves away from the core until it is zero when the front contacts break. The armature then continues to drop away under the action of gravity against the force due to the decaying flux. This continues until the back contacts make and are flexed by the armature weight.

The time taken for the armature to move under the influence of gravity alone is not related to its weight. The weight, however, is important in that, for quick action, it should be small in relation to the contact pressure and the force due to the flux. Nevertheless, the armature must not be made too light because, if it were, the contact pressure at pick-up might be too low. By suitably weighting the armature having regard to the greater force on it when picked up, it is arranged by design that the contact pressure is adequate even at minimum pick-up volts.

It is now clear that to reduce operating time to a minimum it is necessary that

- (1) the relay iron should have low hysteresis loss and low retentivity.
 - (2) the armature movement should be small ;
 - and (3) the armature should be as light as possible consistent with good contact pressure at pick-up.
- (1) and (2) ensure that the difference in inductance between the pick-up and drop-away positions of the armature is small and (3) ensures that the armature inertia is as low as possible.

Relay armatures being pivoted have a radial moment and hence it is usual to refer to the "torque" on the armature (i.e. radius $\times$ force which is generally expressed in inch-ounces) instead of referring to the force on the armature.

It will now be appreciated why a d.c. neutral relay takes much longer to drop-away when shunted than it does to pick-up after the shunt has been removed. In the case of a track relay, this is a serious disadvantage. When a single, short vehicle such as a rail-car passes over the insulated joints between two track circuits, the rear track relay picks up quickly but the forward track relay releases slowly because it is shunted. If the difference in the operating times is great and the vehicle speed is high enough, the two relays may be both in the energised position for a short period of time during which interlocking may be released. If the forward track relay is located at the "striking" end of the track circuit, its drop-away time will be improved because the rail inductance will not be included in the releasing circuit.

The steady current condition of each relay is an important factor. If the steady relay current is high (as with a low drop-shunt adjustment), then the pick-up time will be reduced and the drop-away time increased thus increasing the unguarded period which is the difference between the two. If the steady relay current is not greatly above the pick-up value (as with a high drop-shunt adjustment), the difference between the operating times will be less. This is one argument in favour of a high-shunt adjustment although there are other reasons against this practice.

One method of reducing the difference between the pick-up and drop-away times is to introduce a non-inductive resistance in series with the relay thus reducing the time-constant (L/R) of the whole circuit. The effect of doing this is illustrated in fig. 5 which was prepared from actual tests.

Track and line relays operate under different conditions. Owing to varying ballast resistance, the voltage applied to a track relay may, in wet weather, be reduced almost to the pick-up value at which figure the contact pressure must still be sufficient. For efficient shunting of the track circuit, it is necessary that the drop-away figure should be as high a percentage of the pick-up figure as is practicable. For good sensitivity, low wattage operation is necessary. In B.S. 1659: 1950, it is therefore specified

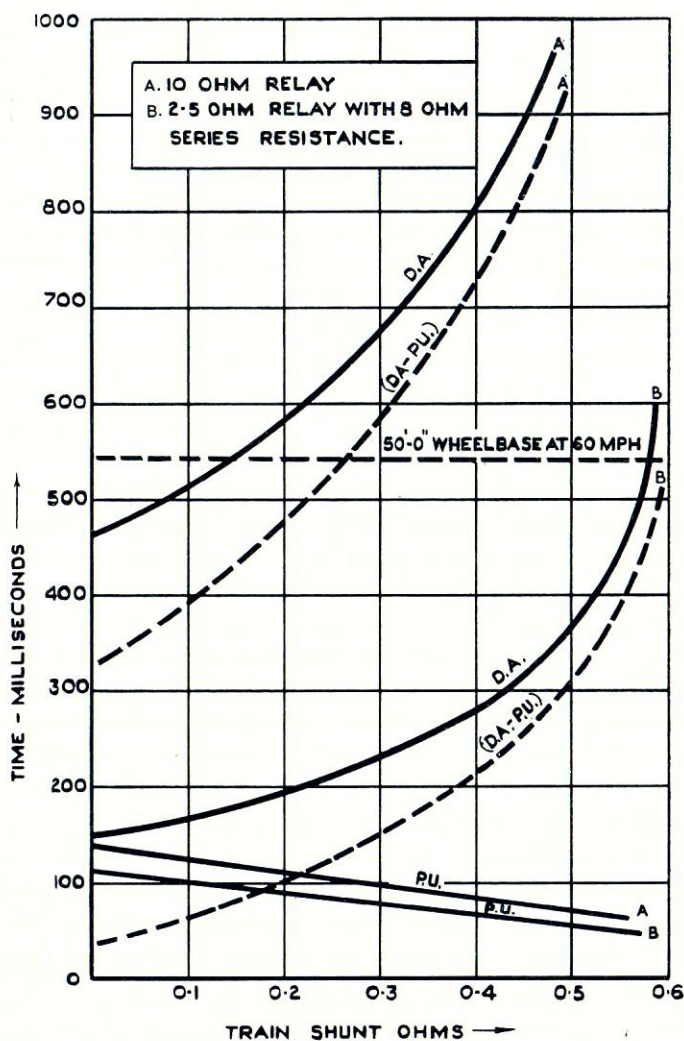


FIG 5

ILLUSTRATING THE EFFECT OF DIFFERENCE BETWEEN THE OPERATING AND RELEASING TIMES OF D.C. NEUTRAL RELAYS

that the percentage release (that is the ratio of drop-away to pick-up current) shall be not less than 68% and that the pick-up figures shall be in accordance with the following table, extracted from Table 3 in the Specification :—

Resistance ohms	Pick-up current milliamperes					
	Contact equipment					
	2 F/B		2F.	2 F/B	4F.	2 F/B
2.25 9	Min.	Max.	Min.	Max.	Min.	Max.
	74	78	78	82	95	100
	37	39	39	41	47.5	50

The maximum permitted wattage consumption calculated from the above table is 13.69, 15.13 and 22.5 milliwatts respectively for 2 F/B, 2 F. 2 F/B and 4F. 2 F/B relays.

Line relays, on the other hand, do not need the same restrictions regarding power consumption and the percentage release is relaxed to 60% for Class A relays and 50% for Class B relays. Table 3 gives the following maximum pick-up figures for line relays :—

Class	Resistance ohms	Pick-up current milliamperes		
		Contact equipment		
		2 F/B 2F. 2 F/B 4 F/B	4F. 2 F/B 2F. 4 F/B	6 F/B
A {	250	Max. 10.5	Max. 12	Max. 14
	1,000	5.25	6	7
B {	250	13	14	17
	1,000	6.5	7	8.5

The maximum permitted wattage consumption calculated from the above table is 27.6, 36 and 49 milliwatts for Class A relays and 42.3, 49 and 72.3 milliwatts for Class B relays respectively for each group of contact components.

Coils of track and line relays are generally arranged so that the higher of the standard resistances is obtained when the coils are connected in series and the lower by parallel connection.

In order to ensure a clean break of the front contacts, B.S. 1659 : 1950 requires that the armature shall develop a return torque of not less than 5.5 inch-ounces for 2-arm relays and 8 inch-ounces for 4 and 6-arm relays. To ensure low contact resistance, minimum front contact pressures are specified to be $\frac{1}{2}$ -ounce per contact at 1.25 times pick-up value and 1 ounce per contact at 1.5 times pick-up value. Back contacts must have a minimum pressure of $\frac{1}{2}$ -ounce per contact when the relay is de-energised.

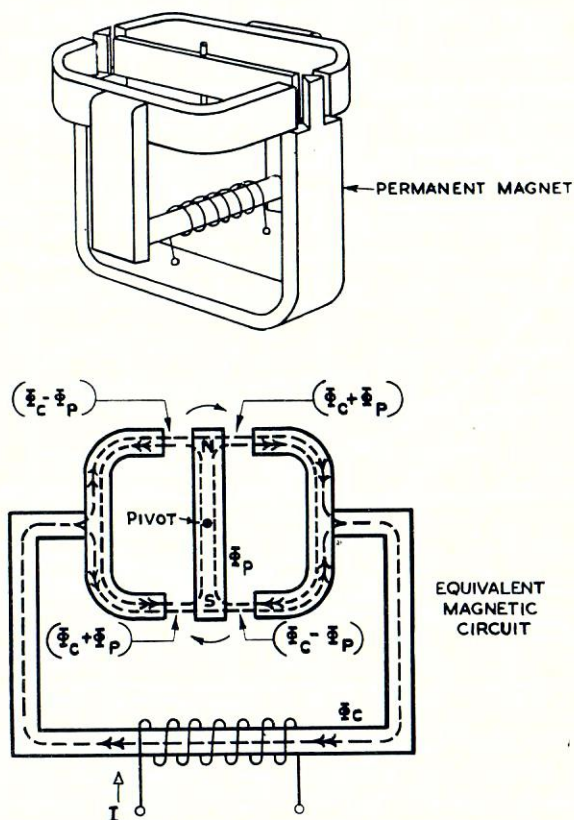


FIG. 6

TYPICAL POLAR RELAY AND EQUIVALENT
MAGNETIC CIRCUIT

3. Polar Relays

Whereas a neutral relay detects the presence of current in the circuit and thus gives only one positive indication the polar relay will detect also the direction of the current and thus give two positive indications.

A polar relay has a soft iron armature which is polarised by a fixed permanent magnet. The armature is pivoted centrally and free to move between the poles of a soft iron magnetic circuit which is capable of being magnetised in either direction by an energising coil. The actual arrangement of the magnetic circuit and its theoretical equivalent is shown in fig. 6.

The permanent magnet performs two functions ; it not only polarises the relay armature but by suitably shaping its poles, it ensures that the armature returns to its true mid-position when the coil is de-energised.

Consider fig. 6. When the coil is energised, each pair of poles (i.e., on one side of the armature or the other) will have the same polarity since they are simply the extension of the electro-magnet poles. There will thus be two North poles on one side of the armature and two South poles on the other. Each end of the armature will be attracted by one pole and repelled by the other and in consequence a torque will be applied to it.

Referring to the equivalent magnetic circuit in fig. 6. At the top or North pole of the armature, the coil flux Φ_c opposes the permanent magnet flux Φ_p on the left but assists it on the right. At the bottom or South pole of the armature, the reverse is the case. There is therefore a torque on the armature tending to move it clockwise. (If the coil current were reversed, the torque would be applied in the opposite direction).

Consider the forces on one end of the armature, say the North pole. The pull to the left is

$$F_1 \text{ which is proportional to } (\Phi_c - \Phi_p)^2$$

The pull to the right is

$$F_2 \text{ which is proportional to } (\Phi_c + \Phi_p)^2$$

Hence the effective force on the armature is

$$\begin{aligned} F &\propto F_2 - F_1 \\ &\propto (\Phi_c + \Phi_p)^2 - (\Phi_c - \Phi_p)^2 \\ &\propto 4 \Phi_c \Phi_p \end{aligned}$$

As the permanent magnet flux is constant, this means that the force on the armature is proportional to Φ_c ; or to the current in the coil.

It will be remembered that in the neutral relay, the force on the armature is proportional to the square of the current.

It is necessary to polarise the armature by an exterior permanent magnet for two reasons. Firstly, there are certain minimum dimensions for a permanent magnet if it is to retain its magnetism and these dimensions would generally be greater than those to be desired for the armature. Secondly, if a permanent magnet were used for the armature it would tend to be retained by its own flux in the position to which it was last operated.

Polar relays of the type described are generally manufactured for a specific purpose and, at the time of writing, no standard specification exists.

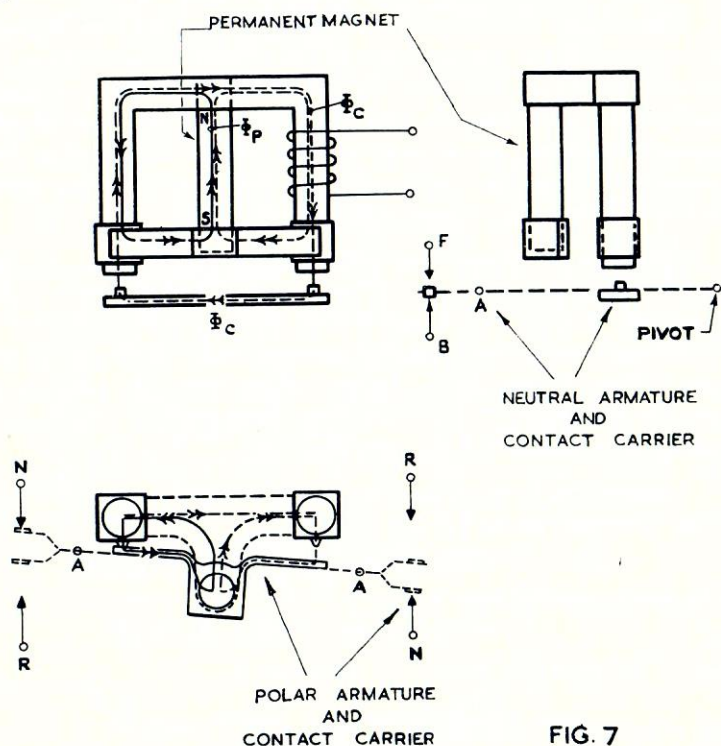


FIG. 7
DIAGRAMMATIC REPRESENTATION OF D.C. NEUTRAL POLAR RELAY

4. Neutral-polar Relays

Polar relays of the type previously described are only suitable for light current circuits such as used for signal repeaters, single line instruments and block instruments. For modern polarised signalling circuits, neutral-polar relays capable of heavier contact pressures are generally used.

A neutral-polar relay has two armatures ; the neutral armature which closes contacts when the coils are energised (in whichever direction) and the polar armature which closes contacts according to the polarity of the current in the coils. The polar armature is designed to remain in the position to which it was last operated.

The magnetic circuit and principle of operation is shown in fig. 7. The essential feature is the third core to which the polar armature is attached. This core is actually a permanent magnet although if necessary it could be an ordinary soft iron core energised by a separate coil to give the polarity desired.

The three cores are attached magnetically at the top so that the flux due to the permanent magnet may have a path through either of the outer cores according to the polarity of the coils. The neutral armature closes on the poles of the outer cores in a similar manner to a neutral relay but the polar armature rotates about the lower end of the permanent magnet and closes on one or other of the poles fashioned on the fronts of the outer cores.

Fig. 7 shows the relay in the de-energised position ; the permanent magnet flux retaining the polar armature in the position to which it was last moved. When the coils are energised, the resulting flux may either assist the permanent magnet flux or oppose it, according to the direction of the current but the neutral armature will be attracted in either case.

If the coils are energised so as to oppose the permanent magnet flux in the outer core or to which the polar armature is closed, the coil flux neutralises the permanent magnet flux. The flux in the other outer core causes the polar armature to be attracted to the opposite side.

Note that whatever the direction of the current in the coils, the coil flux always assists the flux in the permanent magnet itself so that the latter never tends to become de-magnetised in service.

Table 3 in B.S. 519 : 1950 gives the following values for the maximum pick-up current of the neutral armature :—

Relay Resistance ohms	Milliamperes
250	14
1,000	7
2,000	5.5

The minimum release percentage is specified to be 50% and the polar armature is required to operate in either direction at a current not exceeding 80% of the actual pick-up value of the armature. Thus the circuit is always made or broken at the neutral contacts.

The minimum contact pressure on front and polar contact is $\frac{1}{2}$ -ounce per contact at 1.25 times pick-up current and one ounce per contact at 1.5 times pick-up current. The minimum back contact pressure is $\frac{1}{2}$ -ounce per contact when the relay is de-energised.

A.C. RELAYS

Symbols used in the text

B	=	flux density in lines per sq. cm. on d.c. supply
B_m	=	maximum value of flux density in lines per sq. cm. on a.c. supply
b	=	instantaneous value of flux density in lines per sq. cm.
Φ_m	=	maximum value of flux in lines per sq. cm.
ϕ	=	instantaneous value of flux in lines per sq. cm.
E_m	=	maximum value of voltage
e	=	instantaneous value of voltage
I_m	=	maximum value of current in amps.
i	=	instantaneous value of current in amps.
ω	=	angular velocity in radians per second
	=	$2\pi f$
f	=	frequency in cycles per second
π	=	3.1416

Thus at 50 cycles per second $\omega = 314.16$

t = time in seconds from commencement of cycle

Note—At any instant t , the actual value of a sinusoidal quantity is equal to the maximum value $\times \sin \omega t$.

For flux density, $b = B_m \sin \omega t$

For voltage, $e = E_m \sin \omega t$

For current, $i = I_m \sin \omega t$

If the current is not in phase with the voltage these expressions become

$$e = E_m \sin \omega t$$

$$i = I_m \sin (\omega t - \phi) \text{ for a lagging current}$$

$$\text{or } i = I_m \sin (\omega t + \phi) \text{ for a leading current}$$

E_{LV}, I_{LV} = voltage and current induced in vane by Local winding flux Φ_L

E_{CV}, I_{CV} = voltage and current induced in vane by Control winding flux Φ_C

V_L, I_L = Terminal voltage and current in Local winding

V_C, I_C = " " " " " Control "

Trigonometrical Functions

$$\sin A = \cos (90 - A)$$

$$\sin^2 A = \frac{1}{2} (1 - \cos 2A)$$

$$\sin A \sin B = \frac{1}{2} \cos (A - B) - \frac{1}{2} \cos (A + B)$$

PART II

A.C. RELAYS

1. General

The tractive-armature principle used for d.c. relays has only a limited application for a.c. relays because the force on the armature is not constant but alternates at twice the supply frequency.

This can be shown as follows :—

In general, for d.c. or a.c. relays the force on the armature is proportional to the square of the flux density.

Let B = flux density in air gap on d.c. supply

and B_m = maximum flux density in air gap in a.c. supply

Then for d.c. relays, $F \propto B^2$

and for a.c. relays, $F \propto (B_m \sin \omega t)^2$
 $\propto B_m^2 \sin^2 \omega t$

But $2 \sin^2 \omega t = 1 - \cos 2 \omega t$,

hence $F \propto \frac{1}{2} B_m^2 - \frac{1}{2} B_m^2 \cos 2 \omega t$

Thus the force on the armature of the a.c. relay may be considered as being made up of two parts : a constant term ($\frac{1}{2} B_m^2$) and a quantity alternating at double frequency, the mean value of which is zero. Therefore the mean force is $\frac{1}{2} B_m^2$ and since the same force is required in each case we may say

$$B^2 = \frac{1}{2} B_m^2$$

$$\text{or } B_m = 1.414 B$$

This means that to operate a tractive-armature relay on a.c. requires a flux density of 1.414 times the value which would be required on d.c. If the magnetic circuit is not to be saturated, the cross-sectional area may therefore have to be increased in a relay designed to be operated on a.c.

Consideration shows that the armature force on a.c. is reduced to zero every half-cycle. This is shown graphically in fig. 8. Thus the armature tends to release every half-cycle and is therefore subjected to vibration as evidenced by loud hum.

To reduce the vibration a copper band (or shading ring) is often inserted across part of the pole face. This causes the flux to divide into two components, one lagging behind the other, so that there is always part of the flux tending to maintain the armature.

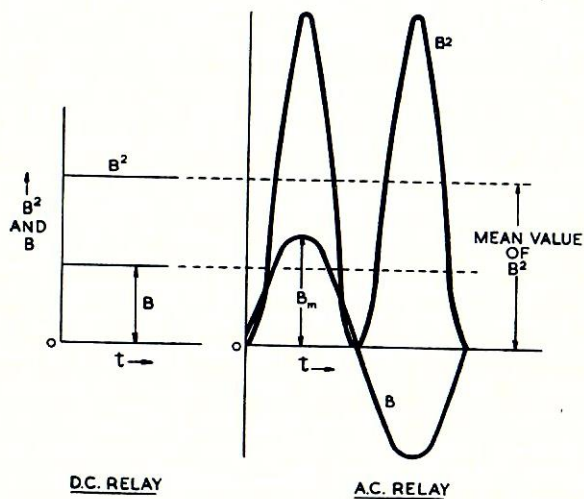


FIGURE 8

COMPARISON BETWEEN D.C. AND A.C. OPERATION
OF A TRACTIVE ARMATURE RELAY

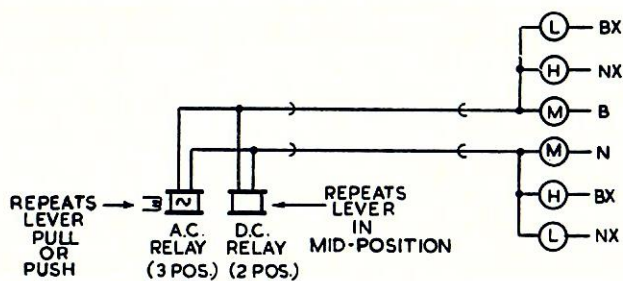


FIGURE 9

CIRCUIT UTILISING D.C. AND A.C. RELAYS TO OBTAIN THREE
POSITIVE CONTROLS OVER ONE PAIR OF WIRES

Even with shading rings, the tractive-armature type of relay is not considered satisfactory for a.c. signalling circuits except for cut-in relays and the like where only one or two robust contacts are required, and the design is not critical.

The impedance of a d.c. tractive-armature relay is high to a.c. and this has sometimes been taken advantage of in circuits similar to that shown in fig. 9. In the circuit shown, the d.c. relay will not respond to a.c. and the a.c. relay which is of the induction-type will not respond to d.c. ; thus enabling three positive controls to be given over one pair of wires.

A.C. signalling relays are usually of the induction type. In this type a pivoted vane or, in one particular type, a cylinder to which the contact carrier is linked is caused to move in a uniform air gap formed by the poles of one or more alternating-current electro-magnets. It will be shown later that the electro-magnets must produce two separate fluxes, differing in phase, which pass through the vane and induce eddy currents therein. The torque on the vane results from the linkage of eddy currents and fluxes. The method by which the fluxes are produced determines whether the relay is of the single-element or two-element type.

Single-element relays are fed from a single source of supply. The two fluxes are produced by the inherent features of the magnetic circuit. Single-element relays are used nowadays solely as 2-position line relays although, before the development of the two-element relay, they were also used as track circuit relays.

Two-element relays have two windings and are fed from two sources of supply each producing one of the fluxes required. They may be designed as 2-position or 3-position relays. The 2-position type is commonly used for track relays in which case one winding, fed from a local supply, is designed to provide most of the energy required to operate the relay. Thus the track circuit has only to supply the other winding with a small amount of energy which permits much longer tracks to be operated than is possible with a single-element relay. In the 3-position type, advantage is taken of the fact that the reversal of one winding of a two-element relay reverses the direction of torque, thus enabling the relay to operate contacts in three positions, viz. Normal, De-energised (i.e., one winding disconnected) and Reverse.

2. Basic Operating principle of a.c. induction relays

Consider a conductor carrying current situated in a magnetic field and at right angles to it as shown in fig. 10. A force will be exerted on the conductor which may be determined as follows :—

$$\text{Force} = \frac{\text{current} \times \text{flux density} \times \text{effective length of conductor}}{10}$$

$$\text{or } F = \frac{I \times B \times L}{10} \text{ dynes}$$

where I = current in amps., B = flux density in lines per sq. cm. and L = length in cms.

It is sufficient for our purpose to say

$$F \propto I \times B$$

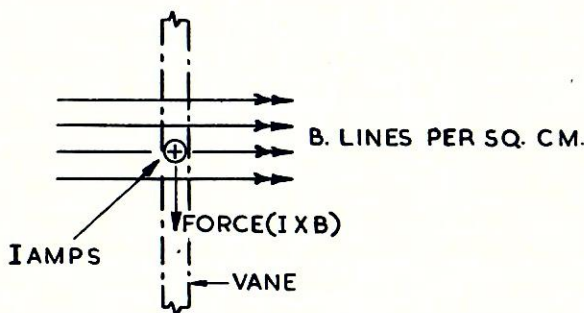


FIGURE 10

FORCE ON A CURRENT CARRYING CONDUCTOR
SITUATED IN A MAGNETIC FIELD

If I and B vary sinusoidally as in an a.c. relay, instantaneous values must be taken. Let the instantaneous current $i = I_m \sin \omega t$. and the instantaneous flux density $b = B_m \sin (\omega t - \beta)$ assuming the latter to lag β behind the former.

We now have

$$F \propto i \times b$$

$$\propto I_m \sin \omega t \times B_m \sin (\omega t - \beta)$$

$$\propto \frac{1}{2} I_m B_m \cos \beta + \frac{1}{2} I_m B_m \cos (2\omega t - \beta)$$

Thus the mean force on the conductor is shown to be proportional to $\frac{1}{2} I_m B_m \cos \beta$ which is obviously a maximum when $\beta = 0$ or in other words, when current and flux are in phase.

Now in a vane relay, the current flows in the vane and is not confined as it would be if it flowed in a single conductor. Never-

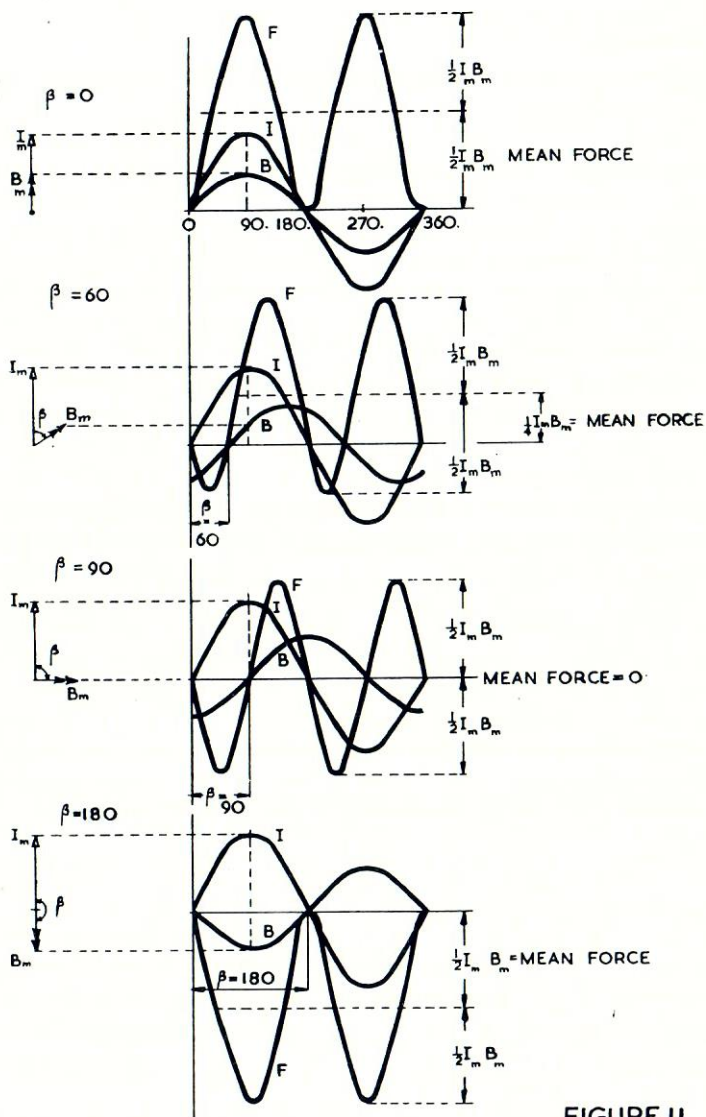


FIGURE II

SHOWING THE EFFECT OF VARYING THE PHASE DISPLACEMENT BETWEEN CURRENT AND FLUX ON THE FORCE ACTING ON THE CONDUCTOR

theless, that portion of the current which interlinks with the flux is proportional to the whole current and so the statement is still correct.

The effect of the phase difference between current and flux should be clearly understood. Fig. 11 shows graphically how the force varies for different values of β . When $\beta=0$, the force is shown to be a maximum and proportional to $\frac{1}{2}I_m B_m$. When $\beta=60^\circ$, the mean force is shown to be proportional to $\frac{1}{4}I_m B_m$ (because $\cos 60=\frac{1}{2}$). When $\beta=90^\circ$, the mean force is zero (since $\cos 90=0$). When $\beta=180^\circ$, the force is again a maximum but is acting in the opposite direction. A phase difference of 180° is obtained by reversing the direction of either current or flux (but not both). It is this fact which enables a 3-position induction relay to be constructed.

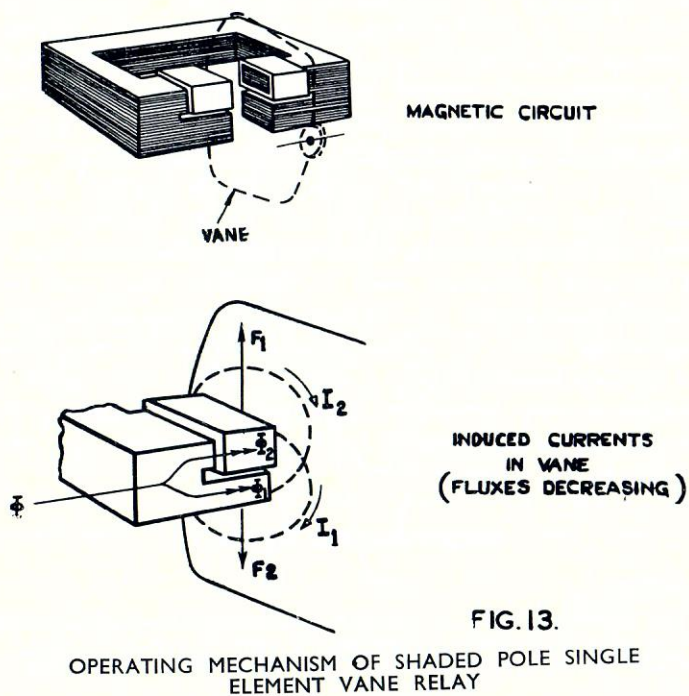
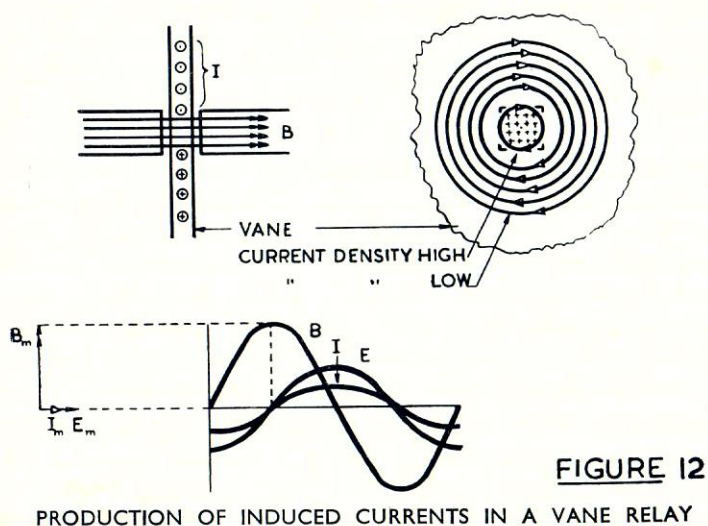
We have now seen how a force is exerted on the vane if it carries a current which is situated in (or passes through) a magnetic field. The simplest manner in which the current can be produced in the vane is to induce it by means of another flux. If an alternating flux is caused to pass through the vane, a voltage will be induced in the vane which will cause a current to circulate. The voltage will lag 90° behind the flux. In general, the current may, for all practical purposes, be regarded as being in phase with the voltage. Fig. 12 shows how the induced currents flow and, graphically, the phase differences between flux, voltage and current. The paths of the induced currents lengthen as the distance from the centre increases and so the highest current density is towards the centre where the path resistance is least.

Thus in any induction relay we have two fluxes and two sets of induced currents. Hence there will be two separate forces acting on the vane. An advantage results from the two forces since the double-frequency term ($\frac{1}{2}I_m B_m \cos (2\omega t - \beta)$) tends to cancel out so that the resultant force is constant throughout the cycle and the disadvantage of the tractive-armature relay does not apply to the induction relay.

Single-element Relays

1. General

The operating mechanisms of single-element relays are similar to those employed for induction-type electrical measuring instruments.



Two forms are in general use, viz.—

1. Voltmeter (or shaded pole) type
2. Wattmeter type

In both types a sector vane is used ; the essential difference between them lies in the magnetic field system. The wattmeter type can also be used as a two-element relay.

2. Operating mechanism of Voltmeter type

Construction. This form of single element relay consists essentially of a laminated iron core with an air gap forming two poles between which an aluminium vane is suspended. Each pole is split and carries a copper shading band on its upper part. A link is attached to the vane to actuate the contact carrier. The general construction of the movement is shown in fig. 13.

The energising coil is usually mounted in halves on each side of the air gap.

Theory of operation. When the coil is energised from an alternating current supply, an alternating magnetic flux is set up in the core. At the poles, the flux splits into two parts ; one part passing through the copper shading bands and the other through the unshaded portion of the poles.

The copper bands act as single turn secondary windings of a transformer, the energising coil acting as the primary winding. By transformer action, a small voltage is induced in each copper band which, owing to the low impedance of the bands, causes a fairly high current to flow. These currents delay the rise and fall of the flux. Thus the flux in the shaded portion of the poles is caused to lag behind the flux in the unshaded portion. The total flux (i.e., that which must be produced by the energising coil) is the vectorial sum of the two fluxes in the air gap. The currents in the shading bands have a demagnetising effect on the flux in that portion of the poles, and it is therefore less than that in the unshaded portion.

When the vane is introduced between the poles, the fluxes in the shaded and unshaded portions induce separate voltages and currents in the vane ; there being the same phase difference between the vane currents as there is between the fluxes producing them.

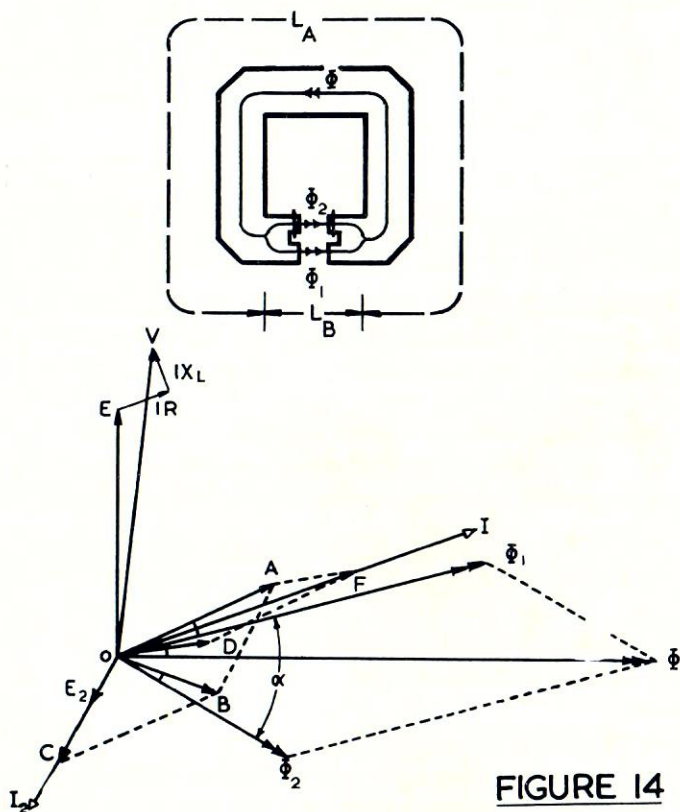


FIGURE 14
VECTOR DIAGRAM OF SHADED POLE RELAY
WITHOUT VANE

Consider first the magnetic circuit without the vane. Fig. 14 shows how the main flux Φ splits at the poles into two components Φ_1 and Φ_2 . The total magnetomotive force, or amp.-turns may be divided into

1. amp.-turns required to produce Φ in length L_A of the magnetic circuit ;
2. amp.-turns required to produce Φ_1 and Φ_2 in length L_B .

In the vector diagrams shown in fig. 14, OA represents the amp.-turns acting across length L_B . Here we have two fluxes in parallel and the value of Φ_1 in the unshaded portion is determined entirely by the reluctance of this branch. The value of Φ_2 however is reduced, as the amp.-turns OA must in this case provide

also for the amp.-turns in the shading band. This means that the amp.-turns available for Φ_2 is the vectorial resultant of OA and the shading band amp.-turns OC which latter lag 90° behind Φ_2 .

The total amp.-turns are obtained by adding vectorially to OA the amp.-turns OD required to produce Φ in length L_A of the magnetic circuit. The exciting current I is in phase with the resultant OF.

Consider now what happens when the vane is introduced between the poles. The eddy currents in the vane set up demagnetising amp.-turns in the same manner as the currents in the shading bands. Thus the amp.-turns OA must now, in one branch, provide for Φ_1 and the eddy currents due thereto and, in the other it must provide for Φ_2 , the eddy currents due thereto and the shading band current. The vector diagram under these conditions is shown in fig. 15A. The voltage induced in the vane due to Φ_1 lags 90° behind the flux vector and if we assume unity power factor in the vane the demagnetising amp.-turns OH will be in phase with the voltage. The magnetising amp.-turns OG lead Φ_1 by a small angle owing to the iron losses. OG is the vectorial resultant of OA and OH. The voltage in the vane due to Φ_2 lags 90° behind the flux vector as does the shading band voltage but the demagnetising amp.-turns due to the corresponding currents is now greater and is represented on the vector diagram by OC. As before, the magnetising amp.-turns OB (for flux Φ_2) is the vectorial resultant of OA and OC. The amp.-turns OC are due to both the shading band current and the vane current. The vane current I_2 is smaller than that due to Φ_1 . For clarity the shading band current and voltage have not been shown in the diagram. The total amp.-turns OF, with which the exciting current is in phase is the vector resultant of OD (for flux Φ for length L_A) and OA.

OE is the induced voltage in the energising winding and is obtained from

$$E = 4.44 \Phi N f \times 10^{-8} \text{ volts.}$$

when N is the number of turns on the winding and f is the frequency. The applied voltage V is the vector sum of E, the resistance drop in the winding IR and the drop due to leakage reactance IX.

As previously mentioned, the forces on the vane arise from interaction between the vane currents and the fluxes in the shaded

and unshaded portions. For clarity, these vectors are shown separately in fig. 15B.

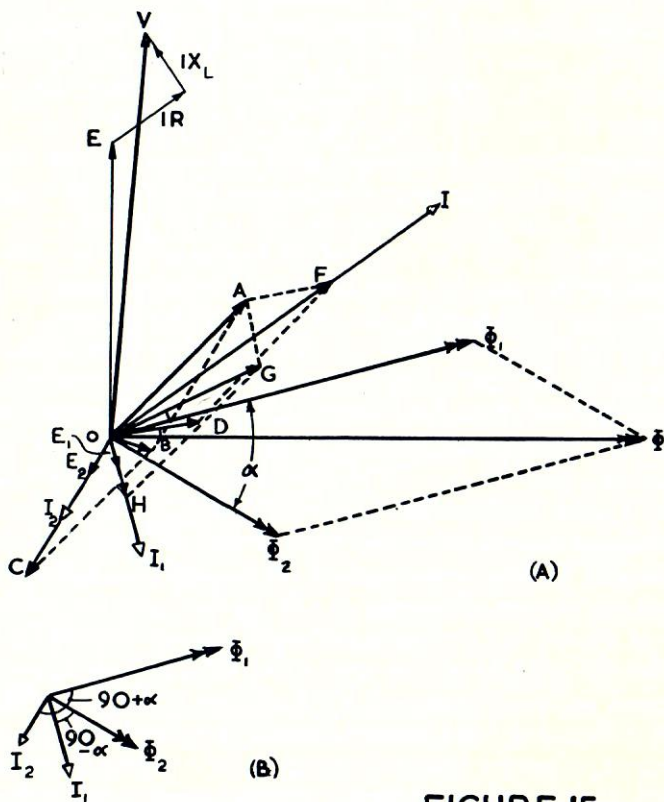


FIGURE 15

VECTOR DIAGRAM OF SHADED POLE RELAY WITH VANE

One force is due to the linkage of Φ_1 and I_2 and the other to the linkage of Φ_2 and I_1 . Fig. 13 shows the paths of the eddy currents. It must be remembered that the directions of currents and fluxes are shown at a given instant when the fluxes are both in the same direction and decreasing. (This assumes that the phase difference between Φ_1 and Φ_2 is less than 90° which is usual).

If the phase difference between the fluxes is α then the angle between Φ_1 and I_2 is $90 + \alpha$ and the angle between Φ_2 and I_1 is $90 - \alpha$. These angles correspond to β in the expression developed earlier.

One force on the vane is therefore

$$F_1 \propto \phi_1 \times i_2$$

and the other is

$$F_2 \propto \phi_2 \times i_1$$

The relative direction of the vane currents is important. For the instant chosen in fig. 13, the direction of that portion of I_2 which interlinks with Φ_1 (to produce F_1) is to the left but the direction of that portion of I_1 which interlinks with Φ_2 (to produce F_2) is to the right although both eddy currents are circulating clockwise. Further consideration of fig. 13 shows that at the given instant, the linkage of Φ_1 and I_2 produces a downward force and the linkage of Φ_2 and I_1 produces an upward force. It must be remembered, however, that because the fluxes and currents vary in magnitude and direction, F_1 and F_2 also vary in magnitude and direction. The net result is a constant thrust on the vane tending to move it towards the shaded portion of the poles.

Taking the flux in the unshaded portion as the vector of reference (fig. 15A) we may say that

$$\phi_1 = \Phi_{1m} \sin \omega t.$$

$$\phi_2 = \Phi_{2m} \sin (\omega t - \alpha)$$

$$i_1 = I_{1m} \sin (\omega t - 90)$$

$$i_2 = -I_{2m} \sin (\omega t - \alpha - 90)$$

A negative sign must be given to i_2 because its direction so far as the linkage with ϕ_1 is concerned is opposite to that for i_1 .

Hence

$$\begin{aligned} F_1 &\propto -\Phi_{1m} I_{2m} \sin \omega t. \sin (\omega t - \alpha - 90) \\ &\propto -\frac{1}{2} \Phi_{1m} I_{2m} \cos (90 + \alpha) + \frac{1}{2} \Phi_{1m} I_{2m} \cos [2 \omega t - (90 + \alpha)] \end{aligned}$$

and

$$\begin{aligned} F_2 &\propto \Phi_{2m} I_{1m} \sin (\omega t - \alpha). \sin (\omega t - 90) \\ &\propto \frac{1}{2} \Phi_{2m} I_{1m} \cos (90 - \alpha) - \frac{1}{2} \Phi_{2m} I_{1m} \cos [2 \omega t - (90 + \alpha)] \end{aligned}$$

The induced vane currents are proportional to their respective inducing fluxes

$$\text{or } I_1 \propto \Phi_1 \text{ and } I_2 \propto \Phi_2$$

whence $\Phi_1 I_2 = \Phi_2 I_1 = K \Phi_1 \Phi_2$ where K is a constant

Hence, substituting, we have

$$F_1 + F_2 \propto \frac{1}{2} \Phi_{1m} \Phi_{2m} [\cos (90 - \alpha) - \cos (90 + \alpha)]$$

$$\text{or } F \propto \Phi_{1m} \Phi_{2m} \sin \alpha$$

but Φ_1 and Φ_2 are each proportional to the current in the energising coils and hence

$$F \propto I^2 \sin \alpha$$

Thus the force acting on the vane is constant and proportional to the square of the current in the coils. Note that if there was no phase difference between the fluxes, $\sin \alpha$ would be zero and no force would be exerted on the vane. The ideal phase relationship is about 45° ; the reason being that if the shading band is increased in dimensions to give a greater angle, the demagnetising amp.-turns so reduce the flux that the force becomes less.

The relation between the fluxes, current and forces is shown graphically in fig. 16. This shows clearly how the forces vary during the cycle although their sum at any instant is constant. If α were made equal to 90° (despite the disadvantage mentioned) the forces would always be additive but if α is less than 90° (as shown) the forces will be in opposition at certain periods during the cycle.

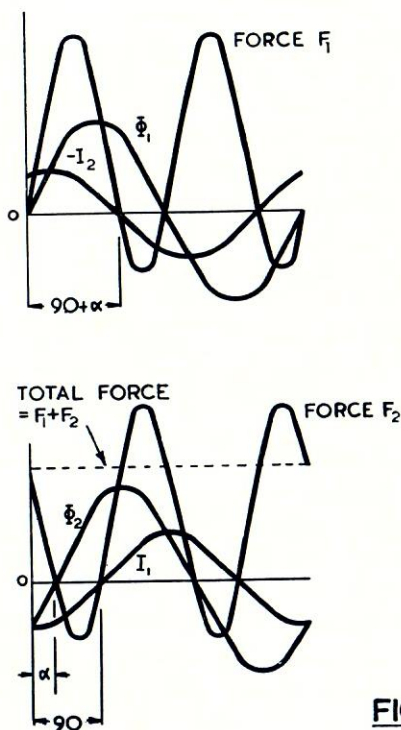


FIGURE 16

FORCES ACTING ON VANE OF SINGLE-ELEMENT RELAY

In drawing the vector diagrams, it has been assumed that the induced currents and voltages are in phase both in the vane and in the shading bands. In the former, the error is negligible as the vane has appreciable resistance as compared with reactance so far as the induced current paths are concerned. In the latter case, the resistance of the bands is lower when compared to their reactance and a small error is introduced by assuming unity power factor. This error is, however, swamped by the magnetic leakage factor which would have to be introduced in an actual calculation. The effect of magnetic leakage is to reduce the effectiveness of the amp.-turns set up in the shading bands so that actual amp.-turns in the vector diagrams must be greater than OC in accordance with the leakage factor.

3. Operating mechanism of wattmeter type

Construction. In this type there are two separate laminated cores mounted on each side of the vane. Each core has a separate winding and each winding produces one of the two fluxes required to cause a force to be applied to the vane.

One core is three-limbed and the other is two-limbed ; the cores being arranged symmetrically as shown in fig. 17.

In a single-element relay the two windings are usually connected in parallel but one winding is then designed to have a higher power factor than the other. In the two-element relay, one is the local winding and the other is the control (or track) winding.

Theory of operation. Referring to fig. 17, winding A causes Φ_A to flow from the central limb through the pole faces of core B to the outer limbs. Likewise winding B causes Φ_B to flow from one limb to the other through the central pole face of core A. Each flux thus cuts the vane twice and is obliged to pass twice across the air gap.

The force acting on the vane, as in the voltmeter type, results from interaction between the induced vane currents and the fluxes but in the wattmeter type the phase difference between the fluxes results from the phase difference between the exciting currents in the two coils.

Consideration shows that there are two entirely separate magnetic circuits in this type of relay each of which may be

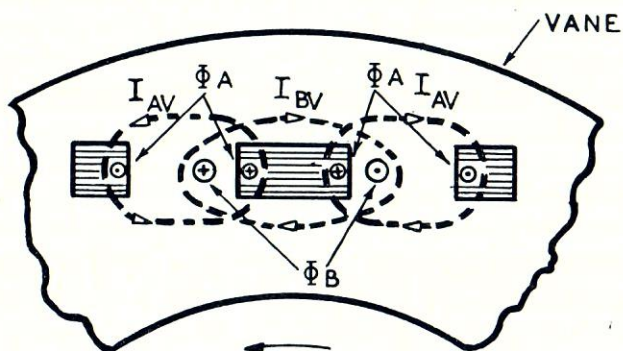
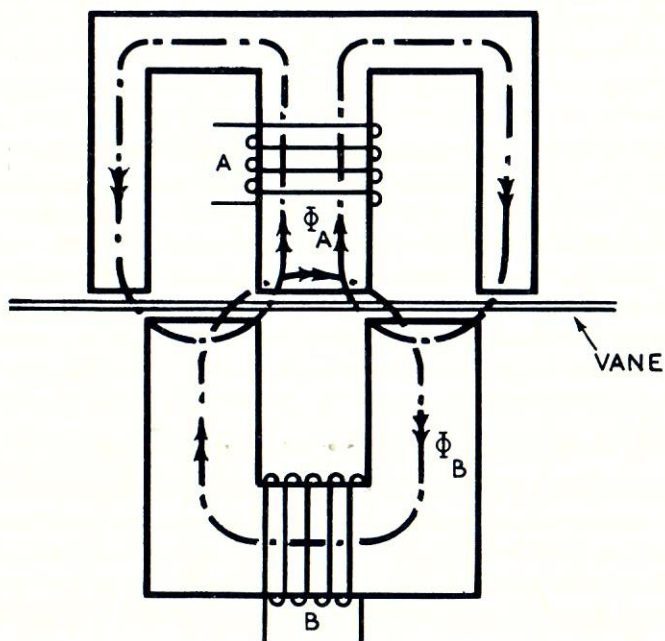


FIGURE 17

MAGNETIC CIRCUIT AND VANE CURRENTS IN WATTMETER
TYPE OF SINGLE-ELEMENT RELAY

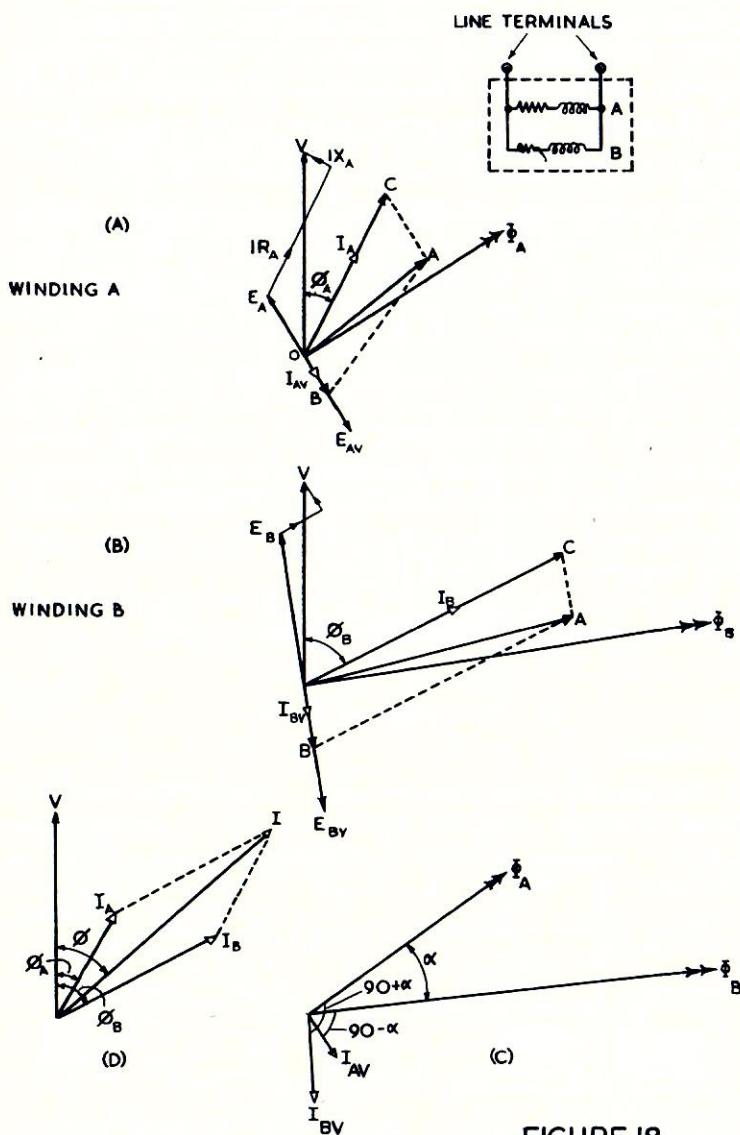


FIGURE 18

VECTOR DIAGRAMS OF WATTMETER TYPE OF
SINGLE-ELEMENT RELAY

represented by the simple vector diagram shown in fig. 18B. If the windings were identical there would be little phase difference between the fluxes and the force on the vane would be small.

In a single-element relay of this type, it is usual to wind one coil with high resistance wire which has the effect, by increasing the IR drop, of raising the power factor of this winding. It also has the effect of reducing the flux since the induced E.M.F. must be less.

The vector diagram shown in fig. 18A illustrates the effect of winding coil A with high resistance wire. Coil B is assumed to be wound with copper wire and its vector diagram—fig. 18B—has been drawn so that the applied voltage OV is in phase with that of coil A.

The force equation is identical with that for the voltmeter type of relay but the losses are greater; firstly because of the I^2R losses in the high resistance winding, and secondly because each flux has to cross the air gap twice and hence more amp.-turns are required than with the voltmeter type. These disadvantages, however, are offset to some extent by the absence of the demagnetising amp.-turns of the shading bands.

The total current and power factor of the relay is obtained by adding vectorially I_A and I_B (see fig. 18D).

Two-element relays

1. General

The essential feature of a two-element relay is that the power should be supplied from two separate sources. There are, therefore, two separate windings in this type of relay known as “control” (or “track”) and “local.”

There are four main forms in general use, viz. :—

- (1) Slotted vane type
- (2) Wattmeter type
- (3) Induction motor type
- (4) Pole face local winding type.

Types (1) and (4) were developed for signalling purposes, type (3) is a simple two-phase induction motor geared to a contact carrier and type (2), as we have seen, is an adaptation of the principle of the induction wattmeter.

Type (1) always has a sector vane, type (2) has a sector vane when used as a 2-position relay and a disc when used as a 3-position relay, type (3) is actuated by a light cylinder and type (4) by a disc.

2. Operating mechanism of slotted vane type

Construction. This type has two separate magnetic circuits. One for the local flux, is so arranged that the flux is caused to pass through the vane twice but in opposite directions. The other, for the controlling flux, is arranged so that the flux passes only once through the vane.

The vane is slotted radially so that currents induced by the local flux are caused to pass between the poles of the control core and interlink with the control flux.

The main features of the mechanism are shown in fig. 19.

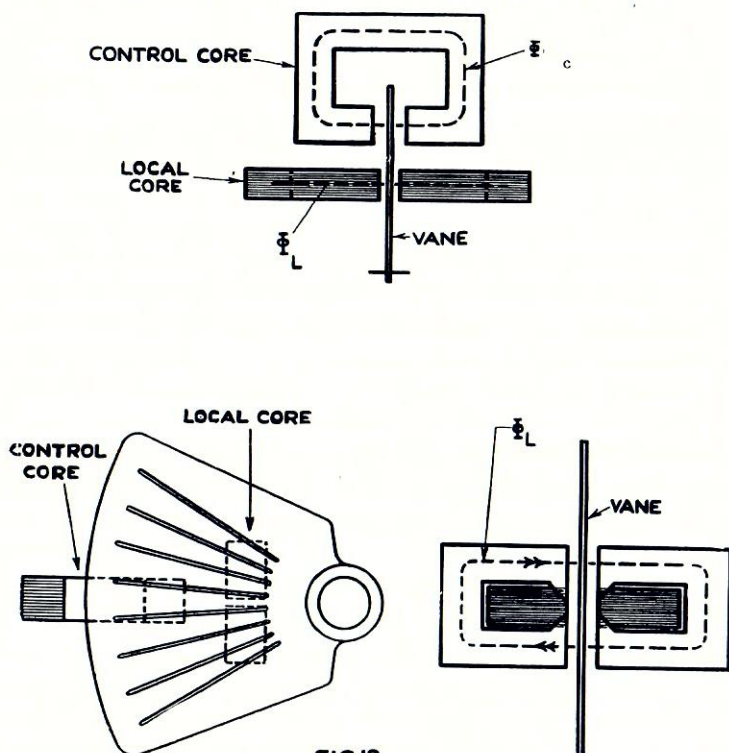


FIG.19.
OPERATING MECHANISM OF TWO-ELEMENT SLOTTED
VANE RELAY

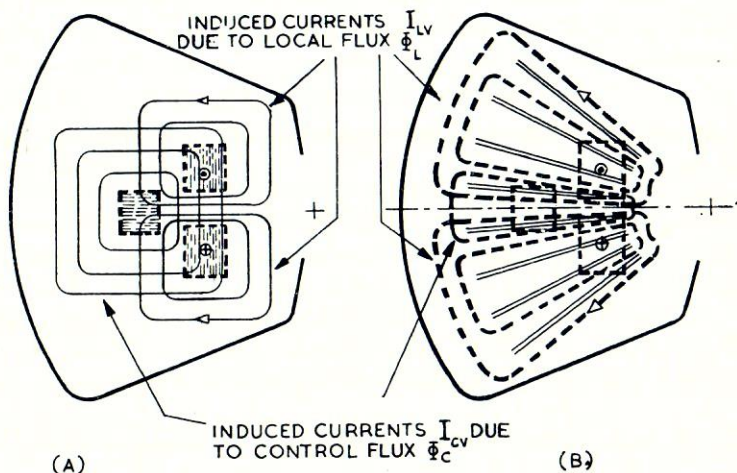


FIGURE 20

EFFECT OF VANE SLOTS ON INDUCED CURRENT PATHS

Theory of operation. Consider first the action of the vane slots. Fig. 20A shows the paths the induced currents would take if the vane was not slotted. I_{LV} is due to the local flux and I_{CV} is due to the control flux. For a force to be exerted on the vane, I_{LV} must interlink with Φ_c and I_{CV} with Φ_L . The construction of the relay is such that the control core must be displaced some distance from the local core and it will be apparent from the diagram, that in each case, only the outer current paths cross the flux. Thus the linkage is small and very little force would be exerted on the vane.

When the vane is slotted as shown in fig. 20B, the currents due to Φ_L are forced to pass across Φ_c and the linkage is thereby greatly increased. The currents due to Φ_c are, however, somewhat restricted and the linkage of I_{CV} with Φ_L is small.

The vector diagrams of the relay are similar to those given in fig. 18 for the wattmeter type of single-element relay, but since the voltages applied to this relay must already have a phase displacement, there is no need for one coil to be specially wound.

Consideration of fig. 20B shows that the path taken by I_{CV} is approximately the same length as that taken by I_{LV} and thus

we may assume that the vane impedance to each of these currents is the same. We have therefore

$$I_{CV} = \frac{E_{CV}}{Z} \text{ and } I_{LV} = \frac{E_{LV}}{Z} \text{ where } Z = \text{vane impedance}$$

Also $E_{CV} = K_1 \Phi_c$ and $E_{LV} = K_1 \Phi_L$
whence $I_{CV} \Phi_L = I_{LV} \Phi_c = K_2 \Phi_c \Phi_L$ where K_1 and K_2 are constants.

This being so, the double-frequency term is eliminated, as in the force equation of the single-element relay and thus we obtain

$$F \propto \Phi_L \Phi_c \sin \alpha$$

$$\propto I_L I_c \sin \alpha$$

The actual value of the vane impedance will vary according to the position of the vane slots in relation to the cores and so the

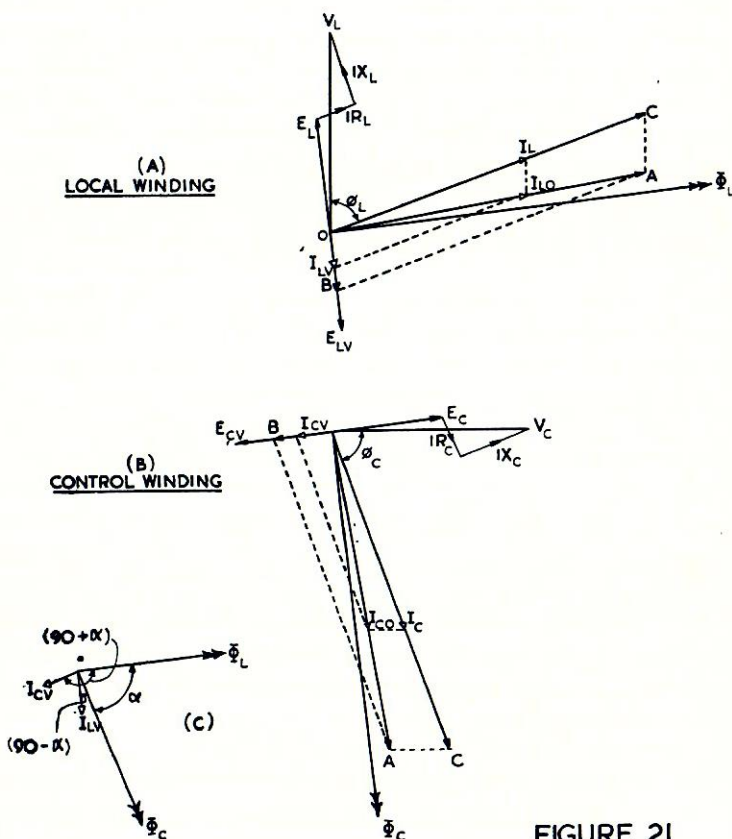


FIGURE 21

VECTOR DIAGRAM OF SLOTTED VANE RELAY

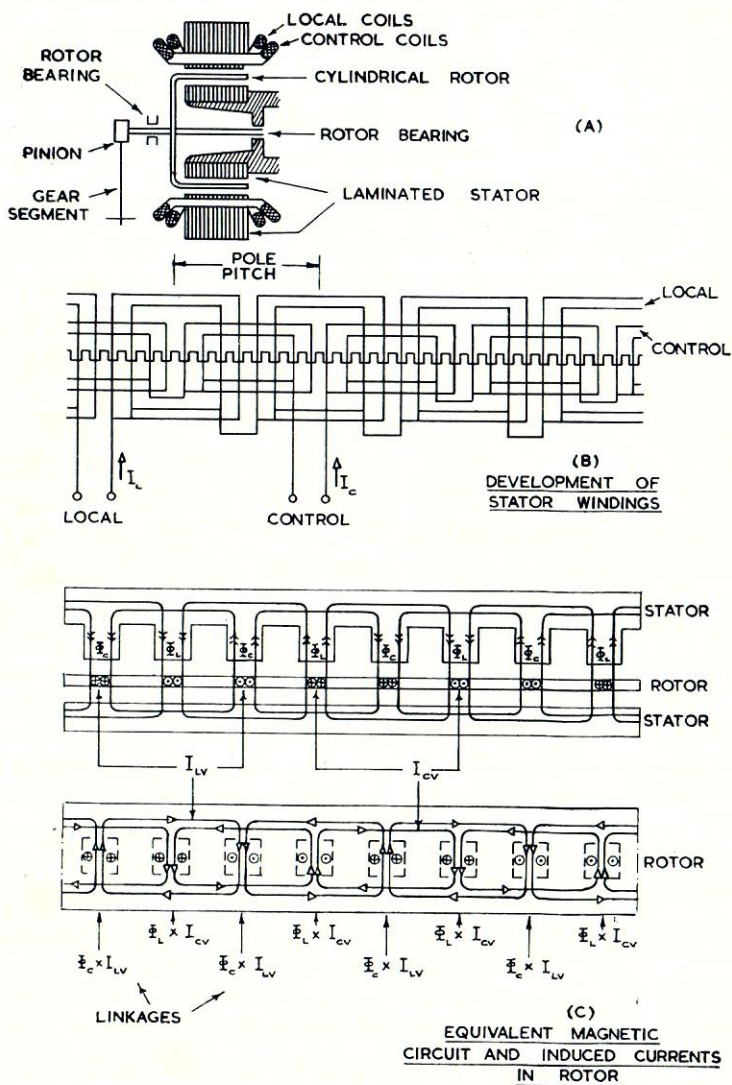


FIGURE 22

OPERATING MECHANISM OF TWO-ELEMENT RELAY, INDUCTION MOTOR TYPE

vane force will also vary as the vane moves. It is probable that in certain positions of the slots the double-frequency term is not eliminated although its amplitude would be small as compared with the mean force.

Typical vector diagrams are shown in fig. 21.

Local winding only energised. In this condition, the local winding continues to induce eddy currents in the vane. These currents produce a flux which magnetises the control core to a small but measurable extent. The effect of this is to cause the local flux to divide in a similar manner to the flux in a single-element relay of the shaded-pole type and thus a small torque is exerted on the vane. This torque varies in magnitude and direction according to the position of the vane. The effect will be greater when the control winding is short-circuited (e.g., when a track circuit is shunted) because the demagnetising amp.-turns due to the control winding will be greater and thus the phase difference between the two parts of the local flux will also be greater.

3. **Wattmeter type**

There is no constructional difference between the single and two-element operating mechanisms of relays of this type. The essential difference is that each winding of the two-element type must be brought out to a separate pair of terminals. In a track relay the phase displacement between the fluxes is produced by exterior means but in three-position relays this is not necessarily so and thus it is sometimes necessary to design one winding to give the phase displacement. In the latter case, there is, electrically, no difference between the single and two-element designs.

4. **Operating mechanism of the induction-motor type**

Construction. The operating mechanism of this type is a simple 2-phase induction motor with a 4-pole stator winding. The actual construction is a little different from a conventional induction motor as the rotor, which is a light aluminium cylinder, rotates in a narrow circular slot in the stator. The rotor is pivoted at each end and a small pinion on its shaft engages with a weighted gear segment to which the contact carrier is linked.

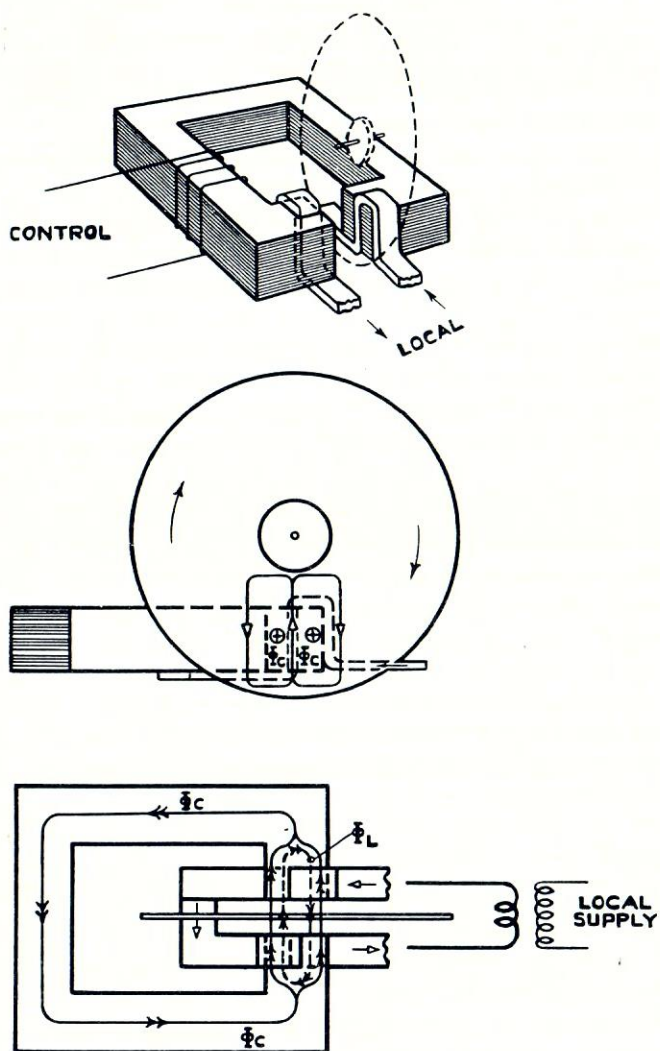


FIG. 23

TWO-ELEMENT VANE RELAY WITH POLE FACE LOCAL WINDING

The general construction of the relay is shown in fig. 22A. The stator winding has 2 coils per pole per phase and as each phase has 4 poles, the stator has 32 slots. A development of the winding is shown in fig. 22B. To close the contact to full compression the rotor revolves about 1.5 times.

Theory of operation. The equivalent magnetic circuit is shown in fig. 22C. Consideration of this figure shows that the flux from each end of the 8 poles produces eddy currents in the rotor and thus there are four sets of linkages between the local flux Φ_L and the eddy currents I_{CV} , and four sets of linkages between Φ_c and I_{LV} . These linkages each produce a force acting on the cylinder in the same manner as in a vane relay. There is a much higher proportion of useful eddy currents in this design than in any other which results in sensitive operation. The times of operation and release are, however, a little greater than in a vane relay.

The vector diagram and force expression are similar to those of any other two-element relay.

5. Operating mechanism of the pole face local winding type

Construction. In the slotted vane relay the eddy current paths are long and the vane is weakened by the slots. This led to the development of a relay in which the local winding consists of a heavy copper strip wound through slots in the pole face of the control core.

The general construction of the operating mechanism is shown in fig. 23.

Theory of operation. The local (pole face) winding is supplied from a transformer which provides a large current at low voltage. The local winding consists of two complete turns ; one on each half-pole. These turns cause a flux to circulate round the two pole faces crossing the air gap twice in a similar manner to the local flux in a slotted vane relay.

The local flux induces two sets of currents in the vane in such a manner that the currents flow together in the same direction vertically in the middle of the pole faces. Linkages of local vane currents with the control flux and vice versa result in a force on the vane.

6. The quadrature component

It has been shown that the force on the vane is proportional to $\Phi_L \Phi_c \sin \alpha$. This means that for ideal operation, the fluxes must have a phase displacement of 90° (because $\sin 90^\circ = 1$). For practical purposes, the phase difference between the local and control voltages may be considered to be the same as the fluxes.

In a track circuit relay, the phase displacement between the local and control voltages is largely governed by the length of the track circuit. Thus in most cases, ideal conditions are not achieved and the voltage applied to the control winding must be increased to compensate.

Now if V_c is the normal compression voltage of the control winding under ideal conditions and V_c^1 is the voltage required to give the same force on the relay when the phase angle between control and local voltages is α then

$$F = K V_L V_c = K V_L V_c^1 \sin \alpha \quad \text{where } K \text{ is a constant}$$

$$\text{whence } V_c^1 = \frac{V_c}{\sin \alpha}$$

Example

The normal compression voltage given on the maker's label of a two-element track relay is 1 volt. If the phase angle between track and local voltages under actual operating conditions is 60° , determine

- the comparative torque if only 1 volt is applied to the control winding and
- by how much the control voltage must be increased to obtain normal contact compression.

Answer

$$(a) \frac{\text{Torque at } 60^\circ}{\text{Torque at } 90^\circ} = \frac{V_c^1 \sin \alpha}{V_c} = \frac{1 \times \sin 60^\circ}{1} = 0.866$$

Thus if the applied voltage remains at 1 volt the torque on the vane would only be 0.866 of that under ideal conditions.

$$(b) V_c^1 = \frac{V_c}{\sin \alpha} = \frac{1}{\sin 60^\circ} = 1.154 \text{ volts}$$

Thus to obtain normal compression with a phase angle of 60° , the control voltage must be increased from 1 volt to 1.154 volts.

The term $V_c^1 \sin \alpha$ is known as the "quadrature component." Its significance is shown in fig. 24. Fig. 24A shows ideal conditions for the purposes of comparison with fig. 24B. This latter figure shows how the applied voltage V_c^1 may be considered as being the vectorial sum of two components at right angles to one another. One component is in phase with the local volts and does not produce a torque on the vane; the other is at right angles to the local volts and produces the whole force on the vane. It is the latter component which is the quadrature component and the effective value of the applied control voltage.

It will be seen from the figure that for the same force on the vane, the quadrature component ($V_c^1 \sin \alpha$) must equal the control volts under ideal conditions (V_c). Note how the control voltage must be increased when ideal conditions are not attained. In drawing the figure, α was taken as 30° which means the the actual control voltage must be twice what it would be if α was 90° .

It will be appreciated that if the quadrature component is caused to change direction the vane will be forced down against the back contacts. Advantage is taken of this fact in a certain type of track circuit by causing the control voltage to alter its phase when the track is shunted to such an extent that the vane force is reversed. The effect is shown vectorially in fig. 24C.

7. Measurement of the relay phase angle

There is a simple method of determining the phase angle of a two-element relay under operating conditions. If the magnitudes of two vector quantities are known together with their vectorial sum, the vector diagram may be constructed and the required angle measured directly.

The apparatus required is a transformer with a ratio of about 50 : 1, a voltmeter and an adjustable metal triangle with graduated sides for constructing the vector diagram. The triangle has one side for the control volts, another for the local volts (as reduced by the transformer) and a third side for their sum. Two sides are extended to form a protractor and pointer respectively to enable the angle to be read off directly.

The purpose of the transformer is to reduce the local volts to the same order as the track volts. If this were not done, accurate

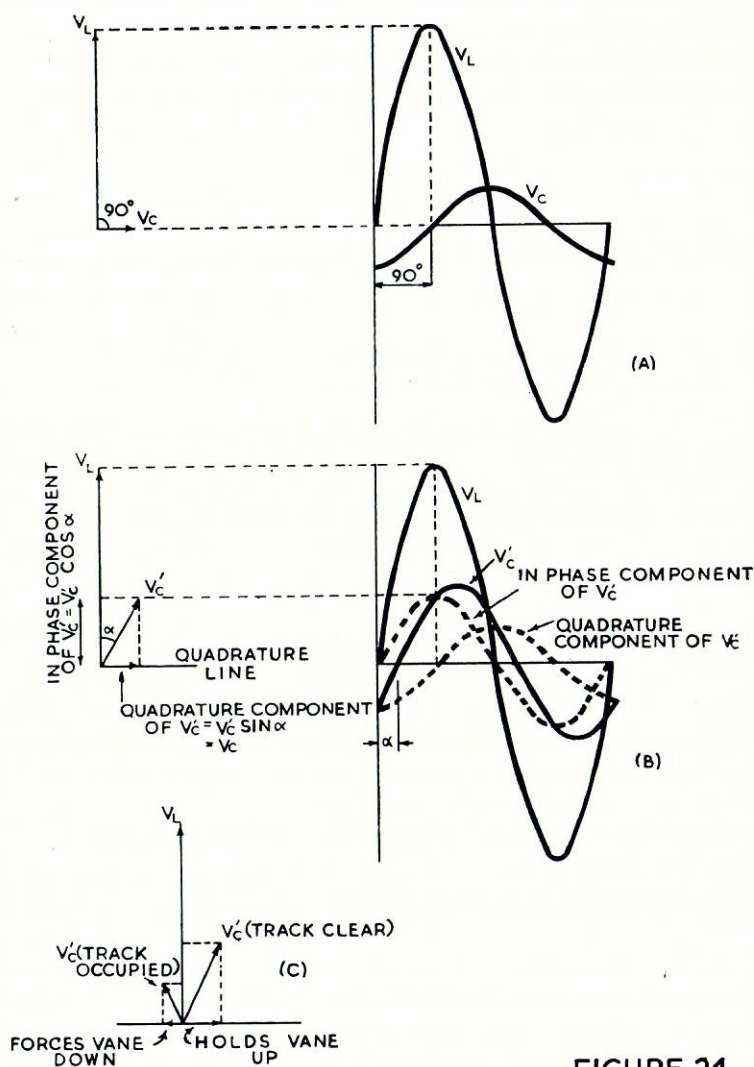


FIGURE 24

QUADRATURE COMPONENT OF CONTROL VOLTAGE IN A TWO-ELEMENT RELAY

results would not be possible since one side of the vector diagram would be about 1 volt, another about 100 volts and the third between about 99 and 101 volts.

8. Resonated control windings

The control winding of two-element vane track relays is sometimes resonated by means of a condenser connected across a special winding on the control core. This winding acts as the secondary winding of a step-up transformer. The step-up ratio enables the capacity of the condenser to be reduced. This result may be shown as follows :—

$$\text{In a transformer, } \frac{E_1}{E_2} = \frac{N_1}{N_2} \text{ and } \frac{I_1}{I_2} = \frac{N_2}{N_1}, \text{ neglecting losses}$$

The overall impedance including the secondary load is

$$\begin{aligned} Z_1 &= \frac{E_1}{I_1} \\ &= \frac{E_2}{I_2} \left(\frac{N_1}{N_2} \right)^2 \\ &= Z_2 \left(\frac{N_1}{N_2} \right)^2 \text{ where } Z_2 = \text{secondary load} \end{aligned}$$

Thus assuming we have a transformer with a step-up ratio of 10 : 1 and that an effective capacity of 10MF is required to resonate the winding, the actual capacity required on the secondary side is found as follows :—

$$Z_2 = Z_1 \left(\frac{N_2}{N_1} \right)^2$$

$$\text{Ignoring resistance } Z_1 = \frac{10^6}{\omega C_1}$$

$$\text{and } Z_2 = \frac{10^6}{\omega C_2} \text{ where } C \text{ is capacity in micro-} \\ \text{farads and } \omega = 2\pi \times \text{frequency}$$

$$\text{Hence } \frac{10^6}{314 C_2} = \frac{10^6}{314 \times 10} \times \frac{10^2}{1}$$

$$\begin{aligned} \text{whence } C_2 &= 10 \times \frac{1}{10^2} \\ &= 0.1 \text{ microfarad} \end{aligned}$$

In a typical design the step-up ratio is 13 : 1 and the capacity provided on the secondary side is 2MF which has an effective

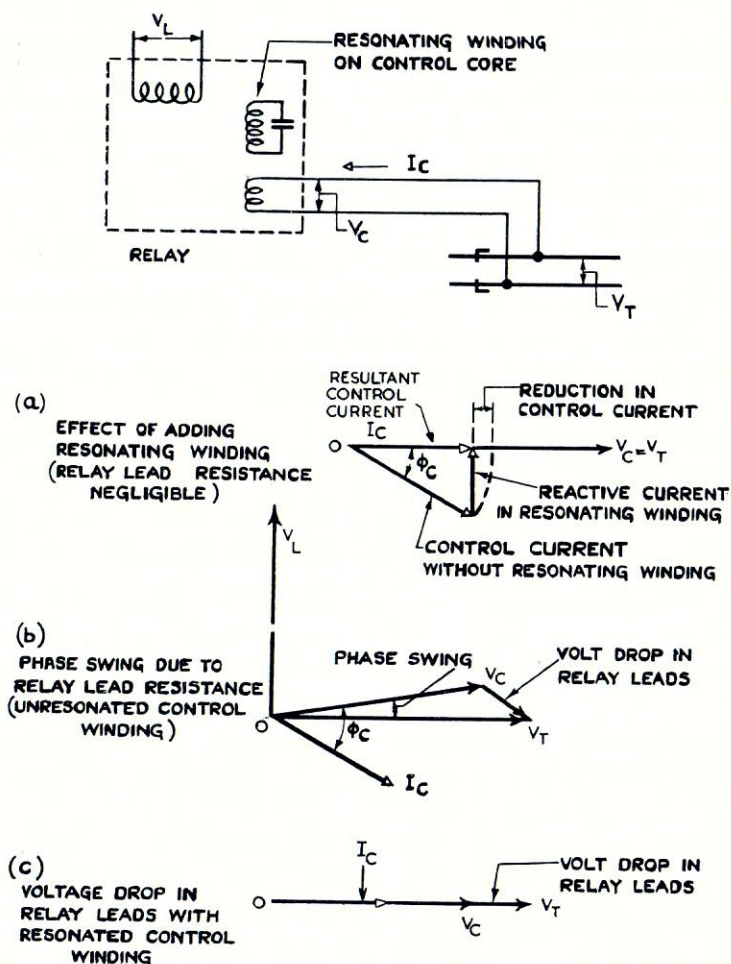


FIG. 25

EFFECT OF RESONATING THE CONTROL WINDING OF A TWO-ELEMENT RELAY

capacity referred to the primary side of $2 \times \frac{13^2}{1} = 338$ MF. (actually

it is somewhat less than this owing to transformer losses).

The purpose of resonating the control winding is to reduce the current required to operate the relay and thus reduce the voltage drop in the rails. It also avoids the phase swing which results from the voltage drop in long relay leads.

Fig. 25 shows the effect of resonating the control winding. Fig. 25A shows how the control current is reduced by the vectorial addition of the leading current taken by the condenser.

Fig. 25B shows how the control volts in a non-resonated relay is caused to have a phase difference with the rail volts owing to the voltage drop in the relay leads. Consideration will show that the local voltage which is in phase with the supply volts at the feed end of the track circuit, has a definite phase relationship with the track volts at the relay end. The effect of the phase swing due to the relay leads is to alter the phase relationship between the control and local voltages which may or may not assist in obtaining ideal (quadrature) conditions. Thus, with long relay leads, not only must the track volts be increased to allow for the volt drop but a further increase is sometimes necessary to compensate for the reduction in the quadrature component due to the phase swing.

Fig. 25C shows how the volt drop in the relay leads of a resonated relay does not cause further phase displacement between the local and control voltages.

PART III

TIME-ELEMENT RELAYS

1. General

A time-element relay is one in which the closing of the front contacts is delayed by about 5 seconds or more. This time lag is too great to be produced by direct-electrical means in relays of the type used in railway signalling.

Thus a time-element relay may be defined as one in which the operating lag is produced by thermal or mechanical means.

There are three common types of time-element relay in common use, viz. :—

- (1) D.C. Thermal type
- (2) D.C. Magnet-driven clockwork type
- (3) A.C. Vane-driven clockwork type.

Time-element relays are generally used to release electrical interlocking in cases where, for reasons of safety, a time delay is essential.

2. D.C. Thermal type

This type is really a heat-operated contact associated with an ordinary d.c. neutral relay.

The heat-operated contact operates on the principle that if two straight strips of metal having different expansion coefficients are secured together, they will exhibit a pronounced curve when heat is applied.

The essential feature of such a contact is, therefore, a bi-metallic strip and a heating element which is wound round the strip. The metals often used for the bi-metallic strip are invar and brass. Invar is a low carbon steel containing 36% nickel and practically unaffected by temperature changes. Brass has a linear coefficient of expansion of 19×10^{-6} per 1°C .

The neutral relay is associated with the thermal contact to record electrically the completion of the heating portion of operating cycle. A typical arrangement is shown in fig. 26.

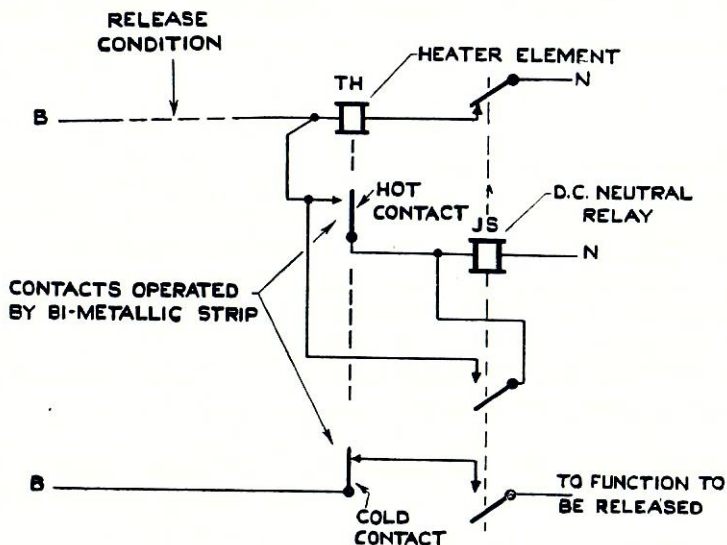


FIG. 26
THERMAL TIME-ELEMENT RELAY

When the release condition is set up, current is applied to the heating element. At the end of heating period, the bi-metallic strip closes a "hot" contact which energises the neutral relay and disconnects the heating element. The strip now cools, breaking the "hot" contact but the neutral relay remains stick fed. When the strip resumes its former position, a normal (or "cold") contact completes the releasing circuit via another contact on the neutral relay.

By having a heating and cooling period in the operating cycle, the bi-metallic strip is returned to its normal condition before a further operation can be attempted. If the release were given at the end of the heating period only, the time of operation might be reduced by a previous operation.

3. D.C. Magnet-driven clockwork type

In this type a reducing gear train is driven by a pair of ratchet magnets. At the end of a pre-determined time interval, a cam operated by the gearing causes a contact to be closed which energises the main contact-operating coil and disconnects the ratchet magnets.

When the supply is disconnected, the clutch magnet which had previously pulled a pinion into the gears to connect the latter to the contact cam, is released thus disconnecting the contact-operating coil.

The contacts are thus quick operating and releasing.

The wiring of the relay is shown in fig. 27.

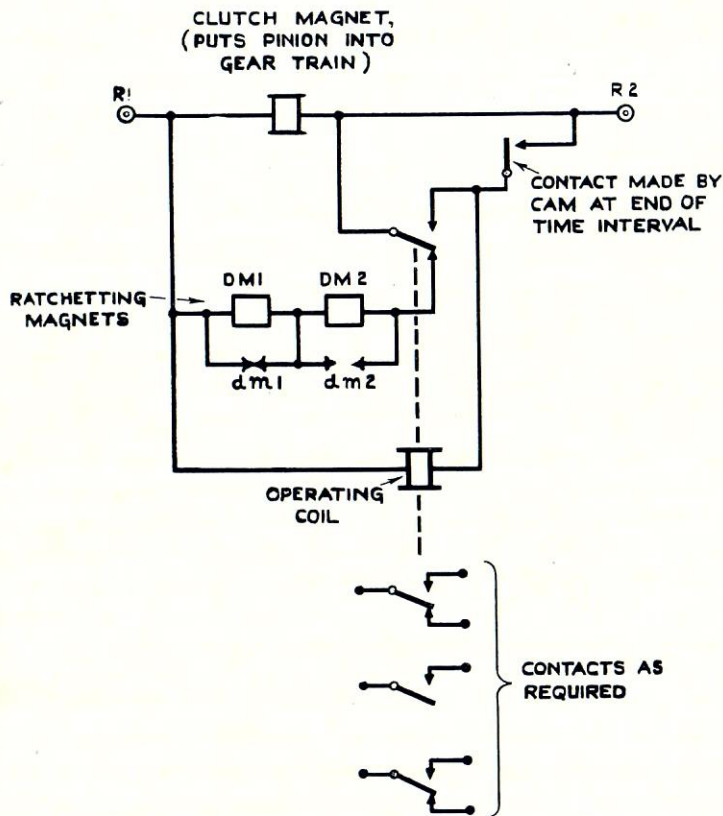


FIG. 27
INTERNAL CIRCUIT OF D.C. CLOCKWORK
TIME-ELEMENT RELAY

With this type of relay, the time lag may be up to 4 minutes. A contact is sometimes included to prove that the contact cam has restored to normal before a subsequent operation can be commenced.

4. A.C. Vane-driven clockwork type

This relay consists essentially of a contact-retarding mechanism connected by a spring link via a gear segment to a large circular vane driven by a single-element relay mechanism. When the supply is connected to the relay coils, the large circular vane completes its full movement immediately and in doing so extends the spring link connection.

The spring link drives the retarding mechanism which consists of a gear train driving a small circular vane revolving between the poles of a permanent magnet which acts as a magnetic brake on the vane.

The spring link drives the small vane at comparatively high speed through the gearing until a toggle releases and operates the relay contacts.

Consideration shows that as the movement of the large vane occupies such a small portion of the total operating time, the effect of voltage or frequency variation on the latter is negligible.

The maximum time lag in this type of relay is about 80 seconds.

PART IV

SLOW-ACTING RELAYS

1. General

Slow-acting relays are so called because contact operation is delayed for a period of the order of one second so as to permit a controlling contact to change over without the relay releasing.

D.C. and a.c. types are available. In d.c. types, the effect is produced electrically but in a.c. types this is not possible and mechanical means must be adopted.

The following d.c. types are used :—

- (1) Slow pick-up and release type
- (2) Slow release type
- (3) Slow pick-up type.

2. D.C. Slow pick-up and release type

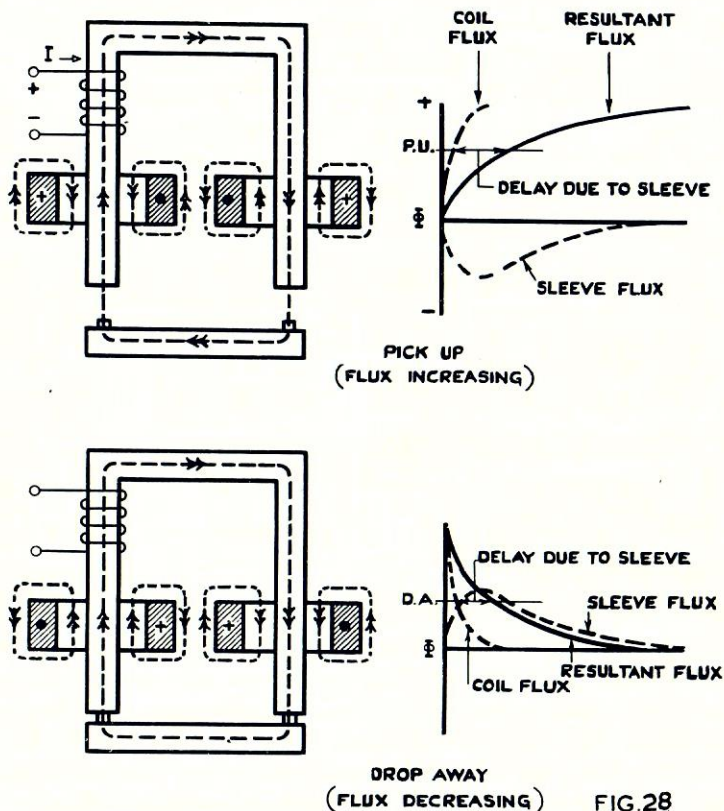
This type has a solid copper sleeve or sleeves on the cores, the purpose of which is to delay the growth or decay of the flux. Fig. 28 shows the principle of the arrangement.

During the build-up of the flux when the voltage is first applied to the coil, eddy currents are induced in the copper sleeves. These currents, by Lenz's law, are of such direction that the flux they produce is in opposition to the coil flux. The build-up of the resultant flux is thus delayed.

When current ceases to flow and the coil flux begins to decay, the eddy currents in the sleeves produce fluxes which endeavour to maintain the coil flux. Thus the resultant flux does not decay as quickly as it would otherwise.

In effect, the introduction of the copper sleeves has introduced additional inductance into the relay circuit without increasing the resistance. The final current is therefore the same with or without the sleeves but the sleeves occupy a considerable amount of winding space—if they are to be effective—and so the coil design is restricted.

The relative directions of the coil and sleeve fluxes should be noted in fig. 28.



D.C. SLOW-ACTING RELAY

FIG.28

Consideration of transient current equations will show that the time taken for the current in the coil to attain the pick-up or drop-away value is proportional to the inductance or L/R resistance ratio. Hence a slow-acting relay must have a high L/R ratio which not only means a fairly large sleeve but also sometimes a fairly low resistance.

The ratio L/R is known as the "time-constant" of the circuit.

3. D.C. Slow-release type

A common method of obtaining a slow-releasing characteristic whilst retaining fast pick-up is to connect a half-wave rectifier across the relay coils as shown in fig. 29.

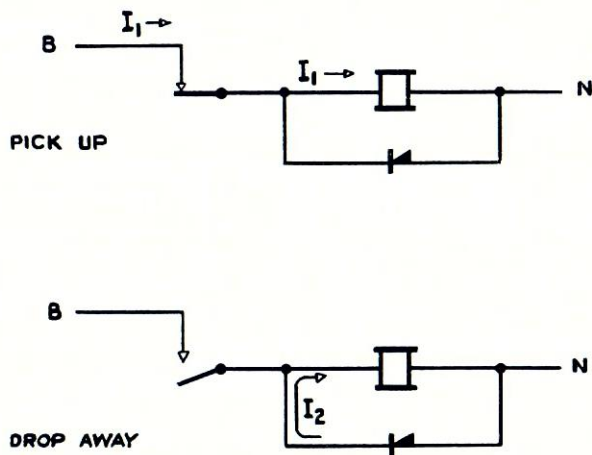


FIG. 29

USING A SINGLE WAVE RECTIFIER TO OBTAIN SLOW RELEASE OF A D.C. NEUTRAL RELAY

When the voltage is applied to the relay coils the direction is such that the rectifier is non-conducting and so the relay picks up in the usual manner. When the relay is disconnected from the supply, however, the voltage induced in the winding by the collapsing flux has a path through the rectifier through which the resulting current flows; thus prolonging the decay of the flux.

The time lag thus obtained is of the order of 250 to 500 milliseconds which is sufficient to maintain the relay when the circuit is momentarily interrupted.

4. D.C. Slow pick-up type

In this type which is shown in principle in fig. 30, copper sleeves are applied to the cores and in addition a magnetic shunt is used to divert flux from the air gap.

The magnetic shunt is positioned immediately below the sleeves so that flux in the shunt may be opposed or assisted by the flux surrounding the sleeves.

During pick-up it is necessary to saturate the magnetic shunt before the flux in the air gap and armature can build up to operating value, but this is delayed considerably because the sleeve flux *opposes* both the coil and shunt fluxes.

During release the magnetic shunt diverts flux from the air gap and is *assisted* by the sleeve flux. This results in a comparatively quicker release.

In order that sufficient flux may flow in the armature to hold it up when conditions are steady, the shunt is of smaller cross-section than either the cores or the armature. The reluctance of the shunt is thus higher and so a sufficient part of the coil flux is forced to flow in the armature.

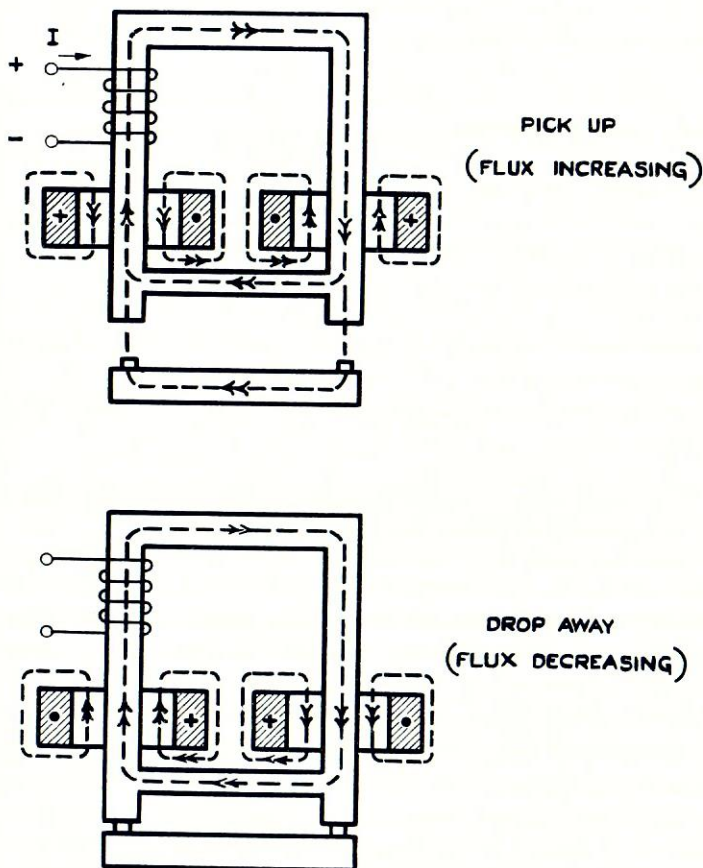


FIG. 30.
D.C. SLOW PICK-UP RELAY HAVING MAGNETIC SHUNT

PART V

MATERIALS USED IN RELAY CONSTRUCTION

1. Magnetic circuit of d.c. Relays

The iron used in the magnetic circuit of d.c. relays must have low retentivity and high permeability. Retentivity is the flux remaining in the iron after the previous magnetisation has reached saturation point and is a measure of the flux which will remain after normal magnetisation. Low retentivity not only avoids the danger of a relay failing to release after de-energisation but it also implies a narrow hysteresis loop which is a necessary requirement if the drop-away/pick-up ratio is to be kept high. It is also a requirement if the operating figures are not to vary considerably according to the degree of previous magnetisation. This difference in operating figures is always present to a small extent and for this reason the B.S. Specification requires that the figures given on the relay label must be determined only after the relay has been energised to four times the rated pick-up value in the working direction. High permeability reduces the amp.-turns required for the iron circuit.

It is also desirable that the specific resistance shall be high in order to reduce the eddy current effect during transient conditions.

Early relays had Swedish charcoal iron cores but, in modern relays, silicon iron (2% silicon) or Stalloy (4% silicon) is generally used because the hysteresis and eddy current losses are less than one half that of the best Swedish iron. It is interesting to note that steel for other purposes does not have a silicon content greater than about 1%. Silicon iron is also used for the yoke and armature.

Permanent magnets for polar and neutral-polar relays are generally made up of cobalt steel (15% cobalt), nickel-aluminium steel (27.5% nickel, 12.5% aluminium) or Alnico (17% nickel, 10% aluminium, 6% copper).

The magnetic properties of steels vary widely according to their chemical composition, mechanical stress, temperature conditions and magnetising force.

2. Magnetic circuit of a.c. Relays

In addition to the general requirements for the magnetic circuit of d.c. relays, the material used for the magnetic circuit of a.c. relays must have low hysteresis loss and low eddy current loss.

Eddy current loss is the energy consumed due to the heating of the core by the eddy currents and it is reduced not only by the choice of high resistance material but also by laminating the core. The effect of the latter is to increase the resistance of the path in which the eddy currents flow. The laminations are generally insulated from one another with varnish although the "skin" produced on the plates by the rolling mills is sometimes considered to be sufficiently insulating.

Hysteresis loss is the energy lost in magnetising and demagnetising the iron.

The exciting current (I_0 in the vector diagrams) has two components. One is the magnetising current which is in phase with the flux it produces and the other is the current which supplies both eddy current and hysteresis losses which is in phase with the magnetising voltage. The magnetising voltage and magnetising current are at right angles to one another.

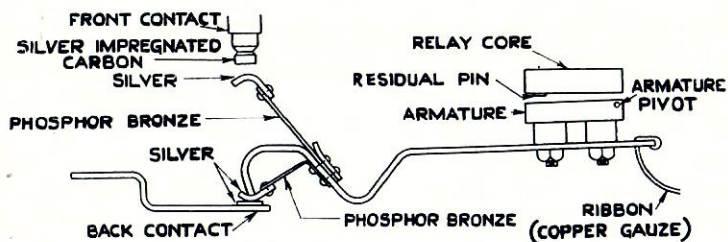
The material generally used for the laminations is known as transformer or meter steel and contains 2 to 4% of silicon.

3. Contacts

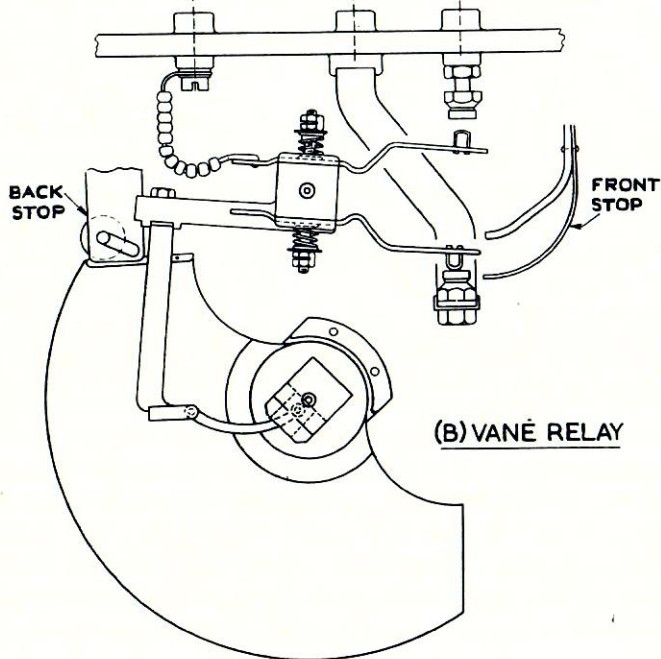
The choice of materials for contacts is governed by two performance requirements. Firstly, welding must not occur on front contacts in the event of an abnormal flow of current, and, secondly, contact resistance at the specified pressures must be, and must remain, as low as practicable.

The usual non-fusible element is carbon. Contacts may be carbon to metal, carbon to carbon or metal to metal; the specified maximum resistances being 0.18 ohm, 0.40 ohm and 0.03 ohm respectively. For front contacts, these values must be obtained at a pressure of $\frac{1}{2}$ ounce per contact for d.c. relays and $\frac{3}{4}$ ounce per contact for a.c. relays.

These figures not only influence contact design but also, bearing in mind the desirability of short travel, the design of the whole of the electrical part of the relay. Another important



(A) DC NEUTRAL RELAY



(B) VANÉ RELAY

FIG. 31.
D.C. & A.C. LINE RELAYS
TYPICAL CONTACT ARRANGEMENT.
TYPICAL CONTACT ASSEMBLIES OF D.C. AND A.C. RELAYS

factor is the necessity for the moving contact to wipe the fixed contact. Moving contact springs must therefore be flexible.

Moving contact springs are generally phosphor-bronze but stainless steel is sometimes used. The contact tip is usually 99% silver ; silver being used in preference to other metals because silver-oxide is a good conductor whereas other oxides are not. For high current circuits, carbon to carbon contacts are sometimes used.

The front fixed contact is always carbon. Carbons are usually impregnated with silver during manufacture to reduce their resistance. In this connection all sources of free sulphur must be eliminated in materials used in relay interiors so as to avoid the growth of silver-sulphide "moss" on the silver-impregnated contacts. For minimum resistance it is necessary that the carbon contact surface should be polished.

Typical designs of contact assemblies are shown in fig. 31. Fig. 31A shows, applied to a d.c. neutral relay, a common arrangement in which the moving contact springs are flexed when in contact with the fixed contacts. Note that the flexible phosphor-bronze strips are attached to heavier section strips which may be set as required during manufacture to ensure the proper line-up of all contacts. The flexing of the front contacts is limited by the residual pin but the back contact flexing is limited by the backing up portion of the heavier strips. The flexing action of the springs causes a wiping movement along the surface of the fixed contacts.

Fig. 31B shows, applied to a vane relay, a design in which heavy section material is used throughout. In this arrangement, the moving contacts are held in position on knife edges formed on the contact carrier by helical springs which compress during the wiping action. Note the vane stops which are essential in a sector vane relay. Contact bounce is eliminated by the roller and slot.

Fig. 32 shows a typical contact assembly for a 3-position relay fitted with independent contacts. The slots in the links connecting the vane to the carrier are provided to avoid contact bounce if the vane overruns when moving to the mid position. No stops are necessary as over-energisation of the relay is guarded by a spring clutch on the vane spindle. Note how the heavier section material is shaped to permit adjustment for contact line-up and how it

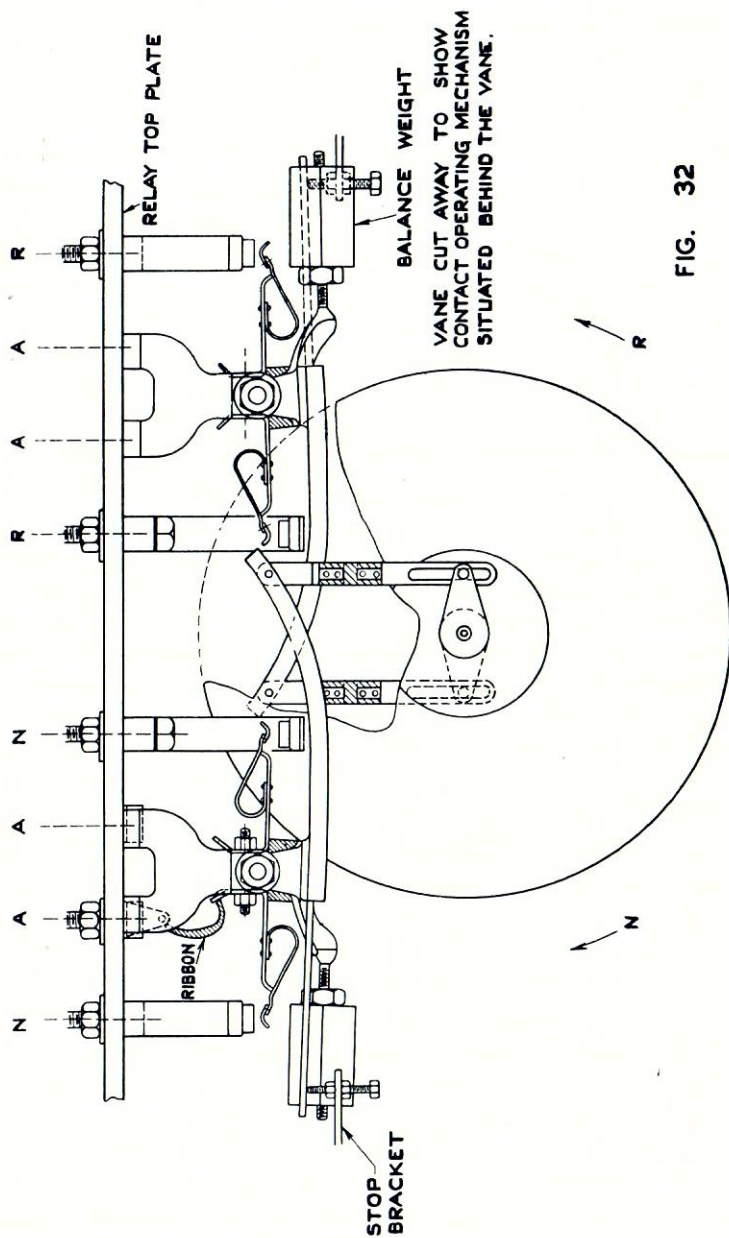


FIG. 32

TYPICAL CONTACT ASSEMBLY OF TWO-ELEMENT VANE 3-POSITION RELAY

forms a backing spring which traps a certain amount of contact pressure so that the specified pressure is available during a shorter movement of the vane than would otherwise be the case. The angle of the contact strip ensures good contact wipe in the shorter movement.

4. Coils

D.C. relay coils are generally wound with enamelled copper wire ; a.c. relays are often wound with fabric-covered wire although enamelled wire is sometimes used.

Coils are vacuum-impregnated with compound to render them moisture-proof. It is important that the compound should be chemically and physically stable to avoid vapour being given off due to heat from the coils and deposited on the inside of the case and thus prevent observation of the moving parts.

5. Bearings

Minimum end clearance is important in relay bearings ; in d.c. relays because the armature carries the contacts and in a.c. relays to ensure clearance of the vane in the air gaps.

In d.c. relays, plain cylindrical bearings in phosphor-bronze housings are common. B.S. 519 : 1950 and B.S. 1659 : 1950 specify that the cylindrical clearance shall be between 0.002-in. and 0.004-in. and that the end play shall be between 0.01-in. and 0.02-in.

For a.c. relays, jewelled pivot bearings are common. The relevant B.S. Specifications require that pivots and bearings shall be cylindrical and that the bearings shall be between 0.003-in. and 0.008-in. larger than the pivots. The end play is specified to be between 0.01-in. and 0.02-in. The bearings consist of a commercial sapphire ring and end plate (the latter for thrust) and the end of the steel vane spindle is highly polished.

Conclusion

It is realised that this booklet has only dealt with the types of relay most commonly met in practice and that there are others which have not been mentioned. It will be found, however, that the operating principle of any other type will be similar to one or other of the relays described and it is hoped that the student will be encouraged to study their theory and set it down for himself.

